



current

THE JOURNAL OF MARINE EDUCATION

Volume 25 • Number 1 • 2009

— special issue featuring —

OCEAN ACIDIFICATION—
FROM ECOLOGICAL IMPACTS
TO POLICY OPPORTUNITIES

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Editorial and advertising offices: **NMEA**, c/o Johnette Bosarge, P.O. Box 1470, Ocean Springs, MS 39566-1470

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current

THE JOURNAL OF MARINE EDUCATION

Volume 25 • Number 1 • 2009

CURRENT LOG *This issue of Current highlights ocean acidification, a term used to describe the ongoing global scale changes in seawater chemistry caused largely by human combustion of fossil fuels. Ocean acidification will have severe consequences for marine life and humankind, and has been nicknamed global warming's "evil twin." The articles in this special issue focus on multiple facets of ocean acidification, including threats to marine organisms, economic implications for fisheries and ecosystem services, and policy options for mitigating negative impacts. Because the dangers posed by ocean acidification are so serious, responsible carbon policy must be implemented immediately at all levels of government and individuals must do their part to curtail carbon consumption, in the hope of safeguarding the future of our oceans.*

Marine Conservation Biology Institute (MCBI) is a nongovernmental 501(c)(3) organization which advocates for the new science of marine conservation biology and for actions that natural and social scientists tell us are essential to maintain the integrity of life in the sea. We analyze scientific research and bring scientists together to examine the most important issues in marine conservation. Our work focuses on diagnosing problems, educating key constituents, and advocating solutions. MCBI's efforts include eliminating destructive fishing practices, establishing marine reserves, fostering the transition to ecosystem-based ocean zoning, and educating others about the threats from ocean acidification to marine biological diversity and ecological integrity.

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MCBI gratefully acknowledges funding from the Education Foundation of America, Edwards Mother Earth Foundation, and Arcadia Trust in support of this publication and of MCBI's other ongoing efforts to address climate change threats to ocean ecosystems.

THE THREAT OF ACIDIFICATION TO OCEAN ECOSYSTEMS

BY JOHN GUINOTTE AND VICTORIA J. FABRY

SEAWATER CHEMISTRY IS CHANGING RAPIDLY BECAUSE HUMANS ARE

burning fossil fuels and releasing carbon dioxide into the atmosphere at unprecedented levels. Since the Industrial Revolution, the oceans have become 30% more acidic and are predicted to become up to 150% more acidic by the end of this century. These chemical changes are occurring so rapidly that many marine species, particularly those that build structures out of calcium carbonate, may have a difficult time adapting quickly enough to survive these changes. This paper reviews known responses of select marine organisms to ocean acidification and potential ecosystem-level impacts.

THE PROBLEM OF HIGH CO₂

For the past 200 years, the rapid increase in atmospheric CO₂ has been, and continues to be, caused by the burning of fossil fuels (e.g., oil and gas), deforestation, industrialization, cement production, and other land-use changes. The oceans absorb much of this excess CO₂ through air-sea gas exchange, which results in changes in seawater chemistry (through changes in the partial pressure of CO₂, pH, alkalinity, and calcium carbonate saturation states). Ocean acidification describes the relative decrease in seawater pH that is caused by oceanic uptake of specific compounds from the atmosphere. Today, the overwhelming cause of ocean acidification is the absorption of human produced CO₂, although in some coastal regions, nitrogen and sulfur are also important (Doney et al. 2007).

Presently, atmospheric CO₂ concentration is approximately 383 parts per million by volume (ppmv), and is projected to increase by 0.5% per year throughout the 21st century, a rate of change that is approximately 100-times faster than has occurred in the past 650,000 years (Meehl et al. 2007). In recent decades, only half of human-produced CO₂ has remained in the atmosphere, the other half has been taken up by the terrestrial biosphere (ca. 20%) and the oceans (ca. 30%) (Sabine et al. 2004). This increase in atmospheric CO₂ has caused a decrease in seawater pH. Since the Industrial Revolution, a time span of less than 250 years, the pH of surface oceans has dropped by 0.1 pH units

and is projected to drop another 0.3-0.4 pH units by the end of this century (Figure 1) (Feely et al. 2008).

The absorption of excess atmospheric CO₂ impacts the ocean's carbonate system with important consequences for calcifying marine plants and animals. Many marine organisms use carbonate minerals (CaCO₃) to form shells, skeletons, and tests, including crustose coralline algae, planktonic organisms (e.g., foraminifera, coccolithophores, and pteropods), warm-water corals, cold-water corals, and a range of benthic organisms (e.g., oysters, clams, sea urchins, and sea stars). When carbon dioxide dissolves in seawater, it forms carbonic acid and several dissociation products (Figure 2). The net effect of changes in this chemical equilibrium (driven by increased absorption of CO₂) is both an increase in the acidity of seawater and a decrease in the availability of carbonate ions, which make it more difficult for marine organisms to build and maintain carbonate structures.

The impacts of these changes in seawater chemistry are further complicated by ocean temperature. The solubility of both calcite and aragonite (which are different forms of calcium carbonate used by marine organisms) is affected by the amount of CO₂ in seawater, which is partially determined by temperature: colder waters naturally hold more CO₂ and are more acidic than warmer waters. The sum of these differences leads to "saturation horizons" in the oceans, which represent the transition depth between waters that are either under- or over-saturated

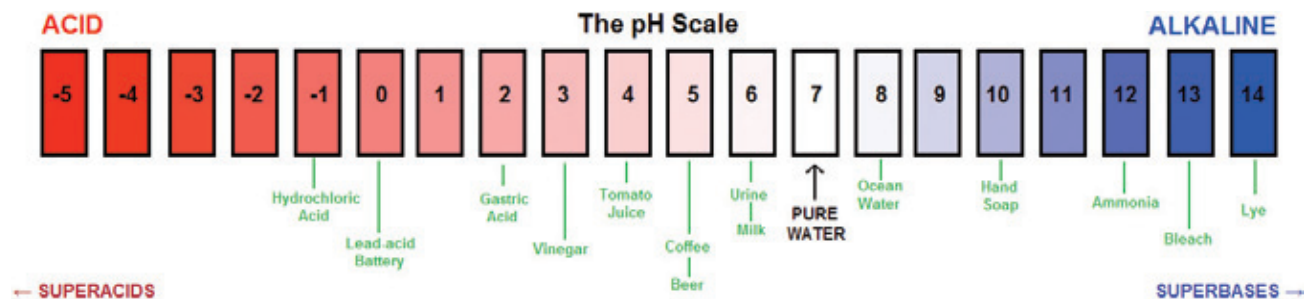


Figure 1. The pH scale. The pH scale is logarithmic, and as a result, each whole unit decrease in pH is equal to a 10-fold increase in acidity. Ocean surface water now has an average pH of 8.1 and is predicted to decrease rapidly with projected rises in atmospheric CO₂.

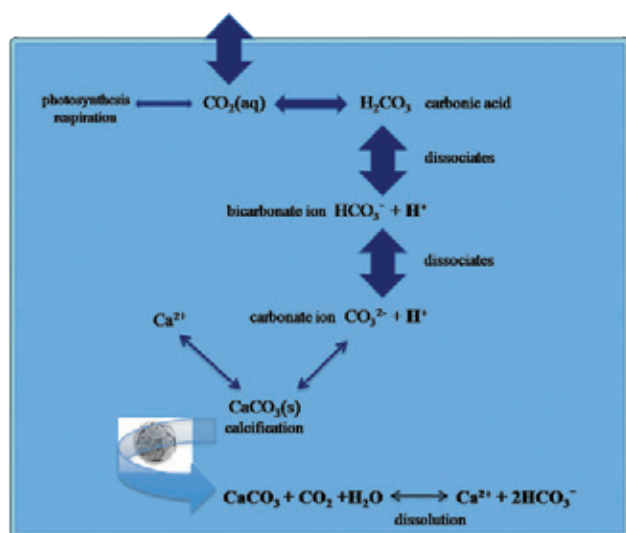


Figure 2. Simplified diagram of the seawater carbonate system. Carbonate chemistry in the oceans involves a complex series of chemical equilibria that are driven by the concentration of various carbon species and are influenced by factors such as temperature and pressure. The dissolution of CO_2 into seawater generates carbonic acid which, in turn, dissociates to release hydrogen ions (H^+). In addition to reducing pH, the excess hydrogen ions bind with available carbonate ions (CO_3^{2-}), thereby reducing the bioavailability of this compound for marine organisms and favoring the dissolution of existing carbonate structures. The net effect of these changes is more corrosive seawater (due to a lowering of pH) and a decrease in the carbonate saturation state of the waters decrease (making it more difficult for organisms to build and maintain carbonate structures).

with respect to calcite and aragonite. In areas that are undersaturated, calcite and aragonite will tend to dissolve. The depth of the ocean's aragonite and calcite saturation horizons determines where calcium carbonate formation by marine organisms is favored (above the saturation horizon) and where dissolution will occur (below the saturation horizon).

The aragonite and calcite saturation horizons of the world's oceans are becoming shallower (i.e., shoaling) due to the rapid uptake of human-produced CO_2 (Feely et al. 2004). Future estimates of aragonite saturation horizon depth, for example, indicate that shoaling will occur in the North Pacific and Southern Ocean within the century (Orr et al. 2005). Many of these areas are highly productive and support some of the world's most important and economically lucrative commercial fisheries.

ACIDIFICATION MAY SPELL TROUBLE FOR MANY CALCIFYING PLANTS AND ANIMALS

Warm-water reef-building corals: The calcification (or growth) response of reef-building corals to ocean acidification has been documented for a handful of species. Current evidence indicates that the calcification rates of warm-water corals will be reduced by 20-60% at double preindustrial atmospheric CO_2 concentrations (Kleypas et al. 2006). A reduction in calcification

of this magnitude could fundamentally alter reef structure (and ultimately, its function as habitat), as growth is dependent on the ability of reef-building corals to accrete (build skeleton) at rates faster than erosional processes can break them down. Weaker coral skeletons will probably result from decreasing aragonite saturation states, which makes the colonies more susceptible to storms and heavy wave action, and increases the erosion rate of the reef foundation (Kleypas et al. 2006).

Crustose coralline algae: Corals are not the only calcifying organisms that are sensitive to ocean acidification. Crustose coralline algae are a critical player in the ecology of coral-reef systems as they provide the "cement" that helps stabilize reefs and are important food sources for sea urchins, parrot fish, and several species of mollusks (Figure 3; Littler and Littler 1984). Laboratory experiments exposing these algae to elevated CO_2 (two-times present-day values), indicated up to a 40% reduction in growth rates, a 78% decrease in recruitment of new larvae, and a 92% reduction in areal coverage (Kuffner et al. 2007).



Figure 3. Crustose coralline algae with a new coral recruit (see center of photo). Crustose coralline algae are ubiquitous red algae that belong to the division Rhodophyta in the order of Corallinales. It is common in rocky tidal areas and in coral reef communities, where it provides food for invertebrates and some fish, and serves as a form of biological "cement." Crustose coralline algae are some of the first organisms to appear on exposed hard substrate, and studies have shown that coral larvae use its presence as a cue to settle and form new colonies. This suggests that these calcified algae are indicators of good habitat for reef corals.

Cold-water corals: Cold-water corals are found throughout the world's oceans and can form biologically-rich ecosystems that provide habitat and nursery areas for many deep-sea organisms, including several commercially-important fish species (Figure 4; see *Current*, Vol. 21, No. 4, 2005, special edition on Deep-sea corals). These ecosystems are bathed in waters that have naturally high levels of CO_2 ; however, more than 95% of cold-water coral reefs occur in waters that are supersaturated with respect to aragonite. Future projections of ocean acidification, however, indicate that 70% of cold-water corals could experience corrosive water conditions by the end of the century (Guinotte et al. 2006).



Figure 4. Bubblegum coral in the waters off Alaska. Bubblegum corals (*Paragorgia* spp.) are cold water corals that inhabit the deep waters of the oceans, well beyond the reach of sunlight. Although they belong to the same phylum (*Cnidaria*) as tropical corals, cold water corals lack symbiotic algae and instead use their small tentacles to feed on plankton and drifting pieces of organic material. Slow growing and incredibly long lived (200 years+), these ancient animals are easily damaged by human activities and are at risk from ocean acidification.



Figure 5. Blue mussel bed in the intertidal of the coast of Cornwall England. The blue mussel (*Mytilus edulis*) is a ubiquitous member of intertidal communities in temperate and polar waters around the world. Able to withstand the dramatically fluctuating conditions of the intertidal realm, blue mussels often form dense mussel beds that provide important physical habitat for a range of other intertidal organisms and serve as an important source of food for intertidal predators such as starfish and dogwhelk. Blue mussels are an important source of food for humans, too, as mussel middens have been found in kitchens dating back to 6000 B.C.

Benthic invertebrates: The effects of CO_2 on benthic invertebrates such as mollusks and echinoderms are currently not well known. Gazeau and colleagues (2007) found that calcification rates of the mussel (*Mytilus edulis*) and Pacific oyster (*Crassostrea gigas*) can be expected to decline by 25% and 10% respectively, by the end of the century. Both species are important to coastal ecosystems and represent a significant portion of global aquaculture production (Figure 5; Gazeau et al. 2007). Early life stages of these species appear to be more sensitive to environmental disturbances than adults. For example, Kurihara et al. (2004) found that ocean acidification affects the fertilization rates of sea urchin embryos and the size and formation of sea urchin larvae.

Plankton: Marine plankton are an important part of the marine food chain upon which all other life in the ocean depends. Several important plankton groups produce calcium carbonate, including coccolithophores (single-celled algae), foraminifera (protists), and pteropods (planktonic snails). The likely effect of ocean acidification has been investigated in only a few species. Experiments with coccolithophores (Figure 6) have demonstrated decreases in calcification rates ranging from 25-66% (associated with partial pressure values of CO_2 of 560 and 840 ppmv, respectively). However, in experiments with *Coccolithus pelagicus*, Langer et al. (2006) found that calcification did not change appreciably with increased CO_2 . Further complicating the issue, experiments with *Calcidiscus leptoporus* suggest that this coccolithophore has the highest calcification rates at present-day CO_2 levels, with malformed structures at both lower and higher CO_2 levels (Langer et al. 2006). In lab experiments with two species of foraminifera, shell mass decreased as water became more acidic (Spero et al. 1997; Bijma et al. 1999), while data for shelled pteropods suggest that shell dissolution occurs in live pteropods within 48 hours under high CO_2 conditions (Fabry et al. 2008).

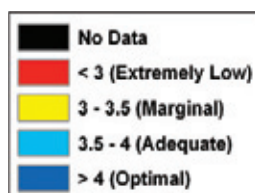


Figure 6a. This is a scanning electron micrograph of a coccolithophore, (*Coccolithus pelagicus*), which is a single-celled marine planktonic alga that creates a calcified shield as a series of ornate plates. These tiny creatures (usually 10-40 μm diameter and much smaller than a grain of sand) are important primary producers in open ocean ecosystems.



Figure 6b. Coccolithophore bloom in English Channel off the coast of Cornwall. Despite their small individual size, blooms of coccolithophores can be extensive, as illustrated by this LANDSAT satellite image. The species responsible for this bloom is *Emiliana huxleyi*, a common and widespread (cosmopolitan) coccolithophore. The shedding of coccoliths into the surface water scatters sunlight, yielding the milky-white turquoise color of the waters seen here, which were called "white waters" by seafarers.

Interestingly, the response of planktonic calcifying organisms to acidifying waters may not be uniform among species or over time. Although current research indicates that most calcareous plankton have reduced calcification in response to higher CO_2 conditions, these have been short-term experiments, ranging from hours to weeks. Little is known about the long-term impacts of chronically high CO_2 , and such experiments may yield complex effects on the growth and reproduction or may induce adaptations that are absent from short-term experiments.



PHYSIOLOGICAL RESPONSES OF MARINE ORGANISMS TO HIGHER CO_2

In addition to impacts on calcification processes, elevated concentrations of CO_2 in seawater affects

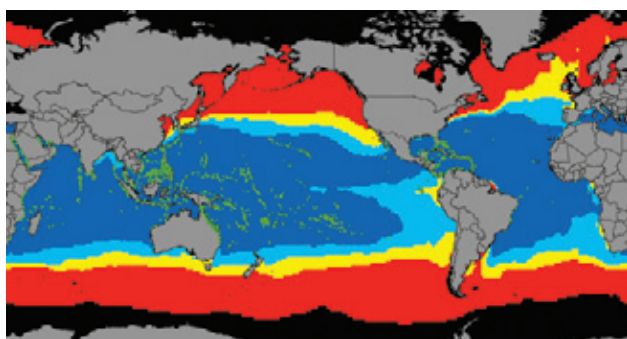


Figure 7a. Surface aragonite saturation state calculated for pre-industrial (year 1870) values of atmospheric CO_2 (280 ppmv). Green dots represent present-day distribution of shallow coral reefs.

the physiology of certain marine organisms. In water-breathing animals such as fish, ocean acidification may reduce the pH of tissues and body fluids resulting in short-term effects on respiration, blood circulation, and nervous system functions and long-term effects on metabolism, growth, and reproduction (Ishimatsu et al. 2004, 2005). Fish in early developmental stages are more sensitive to environmental change than adults, and a small number of studies have shown an adverse negative effect of acidified seawater on fish throughout their entire life cycle (eggs, larvae, juveniles, and adults: Ishimatsu et al. 2004).

Not all marine organisms will be negatively impacted by elevated seawater CO_2 . Short-term experiments with eelgrass indicate that elevated CO_2 increased photosynthetic rates and reduced light requirements (Zimmerman et al. 1997). Longer-term (one year) experiments exposing seagrasses to high CO_2 concentrations resulted in higher reproduction when light was in abundant supply (Palacios and Zimmerman 2007).

COMMUNITY-LEVEL IMPACTS

Seagrasses, coral reefs, and fishes: Seagrass meadows and mangroves provide important nursery areas for juvenile fishes, many of which migrate to coral reefs as adults, and enhance fish diversity and abundance on coral reefs adjacent to these ecosystems (Mumby et al. 2004; Dorenbosch et al. 2005). The net effect of increasing CO_2 on seagrass ecosystems will probably be increased seagrass biomass and productivity. It is probable that an increase in total seagrass area will lead to more favorable habitat and conditions for associated invertebrate and fish species. However, the net effect of ocean acidification on coral reef ecosystems will probably be negative as many warm-water corals will be heavily impacted by the combined effects of increasing sea-surface temperatures (coral bleaching) and decreasing carbonate saturation states of surface waters in the coming decades (Figure 7) (Guinotte et al. 2003). The magnitude of both ecosystem responses to ocean acidification and other environmental changes working together is difficult to predict as are the effects on fish populations and diversity. Predicting the net effects on fish populations is further complicated by the great number of unknowns surrounding the

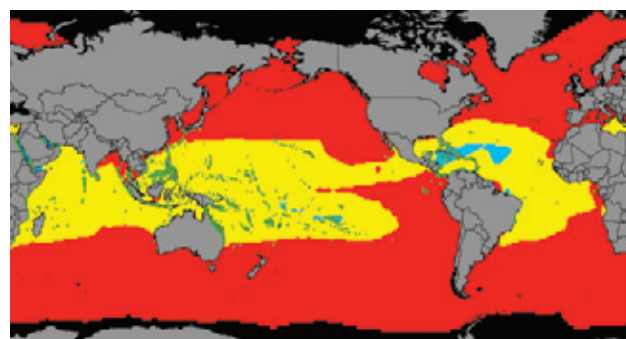


Figure 7b. Surface aragonite saturation state projected for expected increase in atmospheric CO_2 (517 ppmv) for years 2060-2069.

long-term effects of increasing CO₂ on fish physiology, metabolism, and probable shifts in their ranges from ocean warming.

Cold-water corals and fishes: The ecology and species relationships of cold-water coral ecosystems are not as advanced as the state of knowledge for warm-water coral reef systems; however, cold-water coral ecosystems are thought to provide important habitat, feeding grounds, and nursery functions for many deep-water species, including several commercially-important fish species (Mortensen 2000; Fossa et al. 2002). Ocean acidification could have significant effects on fishes and other deep-sea organisms that rely on cold-water coral ecosystems for protection and nutritional requirements. Documenting ocean acidification impacts on coral-associated fishes will be difficult because the ecology of these systems is not well known, but the net effects are likely to be negative as cold-water coral growth, distribution, and area decrease with increasing ocean acidification. Understanding coral-fish associations and the sensitivity of cold water corals to ocean acidification are top priorities for future research.

Plankton: If reduced calcification decreases a calcifying organism's fitness or survivorship, then some planktonic species may undergo shifts in their distributions as ocean acidification progresses. Calcifying species that are sensitive to CO₂ could potentially be replaced by noncalcifying species and/or those species that are not sensitive to elevated pCO₂. If high-latitude surface waters become increasingly more acidic as predicted, pteropods could eventually be eliminated from some regions, with consequences to food web dynamics and other ecosystem processes (Fabry et al. 2008). In the subarctic Pacific, for example, pteropods can be important prey for juvenile pink salmon, as well as chum and sockeye salmon, pollock, and other commercially-important fishes (Aydin pers. comm.). Because Pacific pink salmon have a short, two-year life cycle, prey quality and abundance during the salmon's juvenile stage may strongly influence the pink salmon's adult population size and biomass (Aydin et al. 2005). Ocean acidification may also favor undesirable species. Attrill et al. (2007) reported a significant correlation of increasing jellyfish numbers in the North Sea from 1971-1995 with decreased pH of surface waters and suggest that projected climate change and declining ocean pH will cause jellyfish numbers to increase over the next century. Jellyfish are both predators and potential competitors of fish and may substantially affect ocean ecosystems (Purcell et al. 2007).

CONCLUSIONS

The scientific knowledge base surrounding the biological effects of ocean acidification is in its infancy and the long-term consequences of changing seawater chemistry on marine ecosystems can only be theorized. Most is known about the calcification response for warm-water corals. The potential effects of ocean acidification on the vast majority of marine species are not known. Research into the combined effects of ocean acidification and other human induced environmental changes (e.g.,

increasing sea temperatures) on marine food webs and the potential transformative effects these changes could have on marine ecosystems is urgently needed. It is important to have a firm understanding of the degree to which ocean acidification influences critical physiological processes such as respiration, photosynthesis, and nutrient dynamics, as these processes are important drivers of calcification, ecosystem structure, biodiversity, and ultimately the health of the ocean.

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MATERIAL SUMMARIZED FROM

Guinotte JM and VJ Fabry. (2008). Ocean acidification and its potential effects on marine ecosystems. In *The Year in Ecology and Conservation Biology*, eds. R.S. Ostfeld and W.H. Schlesinger, 320-342. Annals of the New York Academy of Sciences.

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 Figure 6b: Courtesy of Andrew Wilson and Steve Groom
 Figure 7a: Modified from Guinotte et al. (2003)
 Figure 7a-7b Legend: Classification from Kleypas et al. (1999b)

RESEARCHER SPOTLIGHT: GRETCHEN HOFMANN, ECOLOGICAL PHYSIOLOGIST

BY SANDRA BROOKE

WHEN WE ARE TOO HOT OR TOO COLD, WE SHOW IT BY SWEATING AND
going pink or shivering and turning blue. We can even tell quite easily when other mammals like us are feeling the same way, but what about marine animals like mussels or fish or corals? How can we tell when they are feeling stressed from heat or cold? They do not shiver and turn blue...so what exactly do they do?

Dr. Gretchen Hofmann, University of California at Santa Barbara (see inset: *Dr. Gretchen Hofmann*; Figure 1), studies the ways in which environmental stressors affect marine organisms (animals and algae) at the most basic level; in the genes themselves. Long before an animal begins to show obvious signs of stress from temperature, certain genes are busy producing special proteins that can control the kind of damage that the temperature extremes can cause within the cell. These proteins are collectively known as 'heat shock proteins,' and they can provide a great deal of useful information on how animals respond to their physical environment. There are many kinds of other physical stressors that organisms have to cope with, and each triggers specific defense genes ('defensomes') into action.

Some marine species can live almost anywhere while others have a more restricted distribution. A number of physical and biological factors may influence where an organism can live; temperature, salinity, and sunlight are just a few examples. Dr. Hofmann and the members of her laboratory focus on the ecological physiology of marine organisms (in particular kelp, invertebrates such as abalone and sea urchin, and some kinds of fish) to determine the conditions under which stress genes are stimulated (i.e., up-regulated) and how the stress response correlates with the distribution of a species.



Figure 1. Dr. Hofmann pictured with a Pisten Bully, doing research in the Antarctic.

DR. GRETCHEN HOFMANN

Dr. Hofmann was introduced to the concept of global climate changes at an early age by her father Dr. David Hofmann, an atmospheric physicist. Long before the world was aware of global warming, Dr. Hofmann was learning about changes in the atmosphere and the implications for the future of our planet. Dr. Hofmann's scientific background was in biochemistry, but she became interested in biology as her career developed, and has ultimately come a full circle to focus on the effects of global changes in the marine realm. To learn more about Dr. Hofmann's research, visit <http://hofmannlab.msi.ucsb.edu/>.

Expression of defense proteins occurs not just in response to elevated temperature, but also to other environmental stressors such as reduced pH. Often one or more factors can have a 'synergistic effect' where combined effects have more impact than the sum of each one individually. Analysis of these proteins could potentially be used as an early warning system for reefs under duress, or to identify populations of corals that are more resistant to high temperatures or low pH. This kind of research is critical in the face of changes that we expect to occur in the coming years, and Dr. Hofmann and her colleagues will soon begin working on the effects of stressors (including ocean acidification) on a tropical coral reef in Moorea (<http://mcr.lternet.edu/>).

Another of Dr. Hofmann's projects focuses on the ecologically and commercially-important purple sea urchin (*Strongylocentrotus purpuratus*), which lives on the rocky shores of the Pacific coast (Figure 2). Urchins begin creating skeleton during their planktonic larval stages, and experiments conducted in the Hofmann laboratory have shown that reduced pH changes the shape of the larvae. The effects of such changes are unknown, but these results show that future ocean chemistry may significantly alter the physiology of an animal

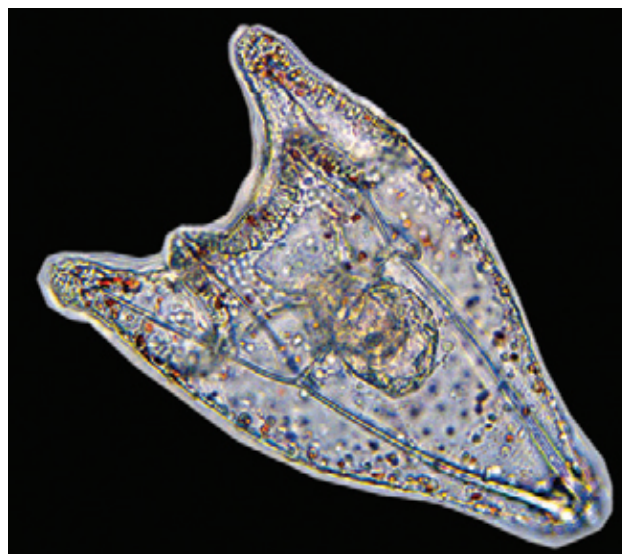


Figure 2. The purple sea urchin (*Strongylocentrotus purpuratus*; left) and its planktonic larval stage (echinopluteus; right), which is only a few millimeters in length.

at a very early stage in the life cycle. For animals that live their adult lives on the substrate, this planktonic stage is their only means of spreading their genes into distant habitats. If larval dispersal is reduced, connection between different populations could be affected, potentially causing areas to become genetically isolated and more vulnerable to extinction.

The purple sea urchin is an excellent model for experiments on gene expression because the entire genome has already been sequenced for this species, thus providing researchers with a complete suite of genes to work on. For most species of interest however, researchers do not have this tool and sequencing through conventional techniques is costly and time-consuming.

THE ACIDIFYING SOUTHERN OCEAN

Some regions are under a more immediate threat from declining ocean pH than others: for example, the Southern Ocean off Antarctica is predicted to be affected by ocean acidification much sooner than other areas, in part because carbonate levels decline during the winter months. Recent research (McNeil and Matear 2008) suggests that winter undersaturation of aragonite may occur in these waters as early as 2030, which is much earlier than originally predicted. This has important consequences for calcifying organisms such as marine pteropods and other small plankton, which form the base of the Antarctic food web. Declines in these species may affect Antarctic fish, penguins, and even some of the whales that travel great distances to feed in these productive waters.

One species of interest to Dr. Hofmann and her colleagues is a very abundant pteropod (small planktonic mollusk) from the Antarctic called *Limacina helicina* (Figure 3). There is a high likelihood that the shell formation and physiology of this important species will be detrimentally impacted by ocean acidification (see inset: *The Acidifying Southern Ocean*). Dr. Hofmann will therefore use a cutting-edge technique called '454 sequencing' (www.454.com) to rapidly generate a DNA sequence for *L. helicina*, which will then be used to study gene expression in this species.

As human activities continue to change the atmosphere of this planet, it is critical that we understand how our actions are

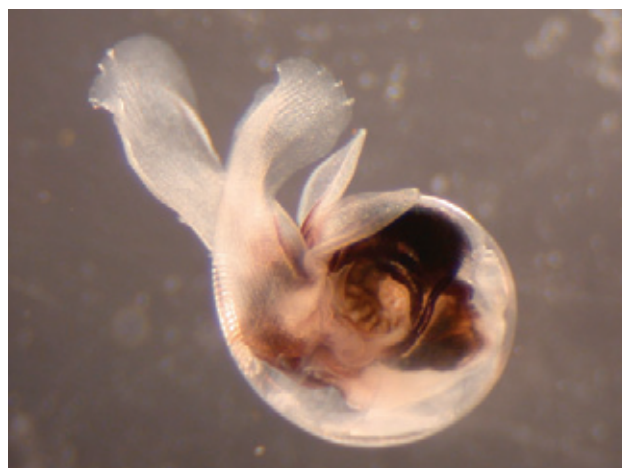


Figure 3. The Antarctic pteropod (meaning wing-foot), *Limacina helicina*, is a small but very abundant planktonic mollusk that looks like a small swimming snail and provides food for many Antarctic animals including filter feeding whales.

affecting the marine environment and the species that live there. Some species will be more vulnerable to changing conditions than others, and there is evidence that even within a species, there are some populations that are more resilient to physical stressors. The technology that Dr. Hofmann and her colleagues are using can potentially identify these critical communities so that they can be protected into the future and provide a stable source of larvae to reseed damaged areas.

SANDRA BROOKE, PH.D., is a Coral Conservation Director at Marine Conservation Biology Institute. She gained her Ph.D. in 2002 from the University of Southampton, U.K. and has worked in several deepwater coral ecosystems in the U.S. and overseas, including the Aleutian Islands, Norwegian Fjords, Gulf of Mexico, and Florida Straits. Her current research projects include coral reproductive ecology, coral biology, and habitat characterization.

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Figure 1: Courtesy of Dr. Anne E. Todgham

Figure 2: Courtesy of Dr. Gretchen Hofmann (adult urchin); Dr. Nann A. Fangue (echinopluteus)

Figure 3: Courtesy of Dr. Gretchen Hofmann

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CHAMPAGNE SEAS—FORETELLING THE OCEAN'S FUTURE?

BY JASON HALL-SPENCER AND ELIZABETH RAUER

IMAGINE YOU ARE AN OCEAN RESEARCHER AND YOU WANT TO STUDY THE ecological impacts of ocean acidification. You know from studies carried out under controlled laboratory conditions that lowered pH can impact the physiology, growth, and development of certain organisms. What you want to know next is how these changes in individual species translate into the direct and indirect ecological changes that occur in the open ocean. Here we summarize the results from a new approach to understanding the ecological implications of ocean acidification: observational studies and in situ experimentation at ocean sites with low pH and high CO₂.

There are a few unusual places in the ocean where carbon dioxide (CO₂) gas seeps through the seabed, rising as bubbles to the ocean's surface and altering surrounding seawater chemistry. To date, most of these so-called "champagne vents" have been found deep in the ocean, at hydrothermal venting sites. A team of international scientists, however, has been studying shallow water vent sites off the Italian coast near Mount Vesuvius, the famous volcano that buried the Roman city of Pompeii in AD 79 (Figure 1). These study sites are more acidic than the surrounding seas, because the CO₂ dissolves into the water; unlike many hydrothermal vents, however, the waters are not superheated and do not contain poisonous sulfur compounds which would otherwise mask the effects of carbon dioxide. This combination of conditions provides an ideal underwater laboratory in which to assess the long-term impacts of low pH on entire marine ecosystems (Hall-Spencer et al. 2008).

LOW PH CAUSES MAJOR ECOLOGICAL SHIFTS

Around the gas vents, seawater pH varies along gradients from 8.2 (normal) to a more acidic 6.6. These gradients dramatically



Figure 1. Bubbles emanating from carbon dioxide vents in shallow waters (0-10 meter depth) off Ischia Island in the Bay of Naples. High CO₂ areas are dominated by macroalgae and calcifiers are absent.

ECOLOGICAL TIPPING POINT

In the acidified waters of this site, a diverse community of corals, mussels, and oysters thrive outside the vent field at normal seawater pH. The ecological tipping point in this area, where the community composition changes dramatically, occurs at a mean pH of 7.8, a value at which calcified organisms are killed by long-term exposures to acidified waters (Figure 2). Corals are completely absent from these waters. Surface ocean waters are predicted to drop to a pH of 7.8 by the end of this century.

impact the surrounding biological communities: in waters with a mean pH of 7.8, the number of species is 30% lower than at sites with normal pH (Hall-Spencer et al. 2008). Seagrasses and algae, including invasive nuisance species, dominate the marine community in the more acidic waters, while species which rely on calcium carbonate to build their shells are completely absent from the acidified waters. The effects on calcified animals, such as snails and limpets, are profound as the corrosive seawater attacks their shells leaving them with paper-thin shells that are easily broken when touched.

These observations at naturally acidified sites provide invaluable information about the ecosystem-level impacts of ocean acidification. They show which organisms, such as seagrasses and invasive algae, are set to benefit from ocean acidification and also reveal major groups of marine life, such as corals and mollusks that are at risk from the current rate of ocean acidification. Such studies demonstrate that increasing CO₂ levels cause the loss of biodiversity and the degradation of marine ecosystems: this should provide added impetus to act quickly to reduce global carbon dioxide emissions and avoid the worst effects of ocean acidification.

JASON HALL-SPENCER, PH.D., is a lecturer in Marine Biology at the University of Plymouth. He conducts applied research to provide policymakers with the scientific information needed to best manage the marine environment, ranging from deep-sea benthos, fisheries, aquaculture, marine protected areas, and biogenic reefs. This year he is working on deep-water coral reefs in the Arctic, new fisheries closures off England, and underwater volcanoes in the Mediterranean.

ELIZABETH RAUER is a Conservation Scientist at Marine Conservation Biology Institute. She holds a Sc.B. in Marine Biology from Brown University, attended Duke University's Beaufort to Bermuda marine science and policy program, and received her Masters of Marine Affairs and Policy degree from the Rosenstiel School of Marine and Atmospheric Science at the University of Miami.

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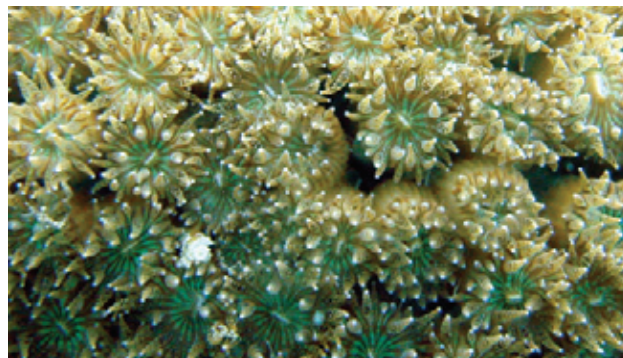


Figure 2a. Demonstration of the dissolution of coral after being transplanted for six months into seawater with a pH of 7.8 (Figure 2a. controls, above; Figure 2b. treatment, below).



Figure 2b.



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DEVELOPING NEW INSTRUMENTATION FOR *IN SITU* EXPERIMENTATION RELATED TO OCEAN ACIDIFICATION—SCALING UP pH EFFECTS FROM THE LAB TO THE FIELD

BY WILLIAM KIRKWOOD AND LARISSA SANO

ALTHOUGH SIMPLE IN CONCEPT, IMPLEMENTING ACIDIFICATION EXPERIMENTS

in the ocean is a daunting task that requires developing relatively complex equipment that must perform in an extreme and unpredictable environment. A group of researchers and engineers at the Monterey Bay Aquarium Research Institute (MBARI) in Monterey, California, however, are tackling just this issue by developing a prototype for an experimental system that will allow for in situ manipulation of local seawater pH. This experimental set-up, called the Free Ocean CO₂ Enrichment experiment (or FOCE), is the new “tool on the block” and allows scientists to move their experimental studies into the ocean.

Two MBARI researchers, Dr. Peter Brewer and Bill Kirkwood, first conceived of FOCE in 2004. The original project was referred to as “Beyond Climate,” and was intended to address a perceived need to inform the public about the connections between the oceans and global climate. The primary motivation for FOCE was to create a multidisciplinary science tool for chemistry that other scientists could use to evaluate the response of bottom-dwelling (benthic) organisms to a slightly more acidic ocean environment.

This effort has evolved into a system that allows researchers to “dial in” a future world based on modeling, science, or policy requirements. FOCE then uses these requests to generate and maintain seawater pH for specified periods of time, thereby allowing for *in situ* (i.e., in place) experimentation. To date, a prototype FOCE

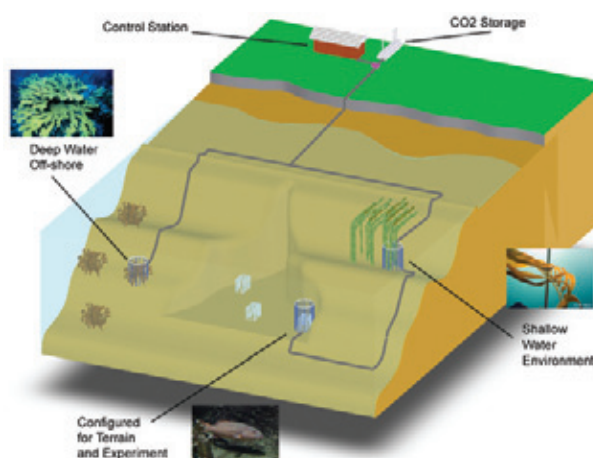


Figure 1. Schematic diagram of the FOCE system.

has been used for short-term simulations (on the order of a few hours) demonstrating that the concept works and that a very tight control of pH is possible *in situ*; the ultimate goal, however, is to develop FOCE into a flexible experimental system that can be used for multi-week experiments in the deep ocean, as well as multi-month experiments in shallow waters, where materials and maintenance can be handled much more easily.

CHALLENGES OF *IN SITU* EXPERIMENTATION OF HIGH CO₂, LOW pH

In developing an *in situ* experimental system, MBARI researchers had to overcome several critical barriers. Some of the unusual engineering challenges faced by FOCE were complicated by working in ocean conditions, including dealing with an incompressible fluid, accounting for ocean currents, dealing with varying ocean chemistries and mixing dynamics, and working with closed loop control variables.

ENGINEERING FOCE

The FOCE concept for implementing multidisciplinary experiments to study the impacts of high CO₂ involves an elaborate configuration of shore-based control stations with underwater experimental chambers. For shallow systems, the CO₂ is provided by either storage tanks or a system of scrubbers when diesel generation is present. The power, communications, and CO₂ use a common path through the land sea interface out to the FOCE experimental sites. FOCE is capable of working with a variety of experimental needs and can provide a pH controlled environment for either contained experiments in which organisms are confined to experimental chambers or open experimental conditions using local flora and fauna such as kelp or corals (see Figure 1).

One of the most basic challenges for FOCE was to figure out the best way to lower pH. Performing a series of experiments with CO₂ and O₂, the researchers found that the *in situ* behavior of solution injection systems in the field didn't mimic the results from laboratory tests. For example, pumping CO₂ into seawater to generate the increased CO₂ predicted for future oceans caused certain problems, including hydrate formation which is related to temperature and pressure (the latter of which is related to depth in the ocean). Perhaps the largest technical problem to overcome was the time delay in the chemical reaction of CO₂ in seawater due to temperature. To get around this, researchers did the original experiments with hydrochloric acid (HCl), but knew that the chemistry in seawater wasn't exactly the same as dissolved CO₂. Once the FOCE concept was proven, the team began to perform experiments using CO₂ instead, which required careful control and monitoring of the amounts emitted into the ocean while also considering ambient environmental conditions.

Another challenge the engineers and researchers faced was how to maintain a decreased pH level for an extended period of time. Throughout most of the ocean, pH values do not vary much. Under field conditions, however, CO₂ reaction rates vary substantially with temperature: at colder temperatures, it takes longer for the injected CO₂ to equilibrate with surrounding waters. At two degrees Celsius, for example, this equilibration reaction can take as long as two minutes and there is a long time delay for these chemical reactions to occur. Because the researchers want to maintain a consistently low pH, they must account for these lag times between when the CO₂ is injected into the water and when it will react to generate the excess hydrogen ions. To overcome this obstacle, the engineers needed to design a system that would measure the ambient seawater pH and correct the rate of CO₂ injection in order to bring about a stable future world ocean within the FOCE system. In contrast, when FOCE is used for studies in warmer waters (for example, surface waters in the tropics), the same reactions will occur almost instantaneously and the CO₂ injection system will need to be more responsive.

AND INTO THE FIELD

The next FOCE prototype will be employed for a biological experiment in the deep waters of the Monterey Bay, off the coast of central California (Figure 2). The new FOCE will be plugged into the Monterey Accelerated Research System (MARS) cabled observatory, located at a depth of over 900 meters (or 2,950 feet; www.mbari.org/mars/Default.html). The observatory will demonstrate several new features for FOCE, including cameras, lights, data access anywhere directly from FOCE, and the addition of a science port to allow remote control of FOCE by scientists back at their desk top. These conditions will be the most challenging to date and demonstrate the utility of developing a system with an intentionally flexible design: each FOCE system can be designed around site specific and experimental conditions. This is one more way in which FOCE is unique

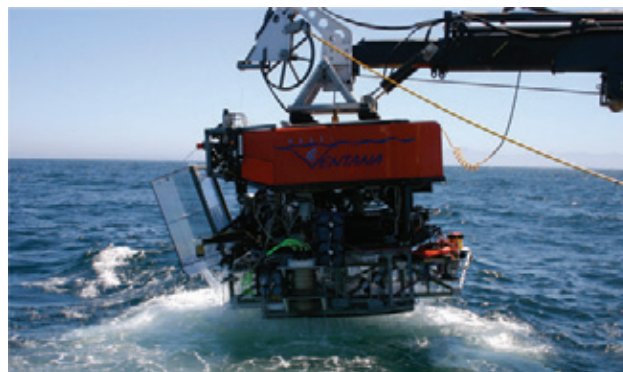


Figure 2. Testing of the new deep water FOCE being completed in the spring of 2008.

since most experimental devices are designed to perform the same under a variety of conditions. FOCE, however, is more of a system or operational concept than a device, and FOCE will look like something different depending on the science needs. Despite this, its overall objective is the same: to solve the CO₂ problem for *in situ* marine experiments.

The FOCE systems are extremely flexible and the concept is anticipated to be useful in a wide variety of research applications. Currently, the most pressing interest is in using FOCE to study upper water column and nearshore areas, primarily coral reefs and estuaries. For example, plans are underway to integrate a FOCE system into an observatory that is being developed at Heron Island on the Great Barrier Reef and there is mounting interest in developing a FOCE system to study ocean acidification impacts to fjords.

For more information about FOCE, please visit our website at <http://www.mbari.org/highCO2/foce/home.htm>.

WILLIAM ("BILL") KIRKWOOD is the Associate Director of Engineering at MBARI and has worked on engineering designs for the remotely operated vehicle *Tiburón* and the autonomous underwater vehicle *Dorado*. Prior to joining MBARI, he was a group leader at Lockheed Missiles and Space Company. Bill has worked with Dr. Brewer on greenhouse gas and fossil fuel related projects for 12 years, enjoying developing technologies for working in the ocean that addresses questions relevant to science and society.

LARISSA SANO, PH.D., is a Senior Scientist at the Marine Conservation Biology Institute, where she works to improve the use of science in promoting the conservation of ocean ecosystems. Larissa received her Ph.D. from the University of Michigan and her M.S. from Oregon State University.

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OCEAN ACIDIFICATION'S IMPACT ON FISHERIES AND SOCIETIES: A U.S. PERSPECTIVE

BY SARAH R. COOLEY AND SCOTT C. DONEY

MANY VALUABLE COMMERCIAL FISHERIES AND AQUACULTURE FACILITIES

harvest ocean shellfish (e.g., clams, scallops) and crustaceans (e.g., lobsters, crabs) that form calcium carbonate shells. These animals, along with corals, may be particularly sensitive to changes in seawater chemistry driven by human fossil fuel use. Finfish may also be affected indirectly owing to loss of prey and habitat. Ocean acidification impacts could decrease future fishing revenues and harm communities that depend economically and culturally on marine resources.

In many parts of the United States, the word “seafood” is nearly synonymous with carbonate shell-forming marine species—shellfish like oysters, clams and scallops, and crustaceans like lobster, crabs, and shrimp. Adults and juveniles of these very economically valuable animals, along with less familiar shelled creatures like sea urchins, planktonic snails called pteropods, and some types of phytoplankton, are food for a variety of predators and fuel food webs. Commercial harvests of shellfish, crustaceans, and finfish sustain seafood industries that support many coastal economies. If ocean acidification slows the growth of marine organisms’ carbonate shells and skeletons, it will endanger many individual plants and animals, whose declines will in turn harm entire marine food webs, aquatic environments, and economies (Doney et al. 2009).

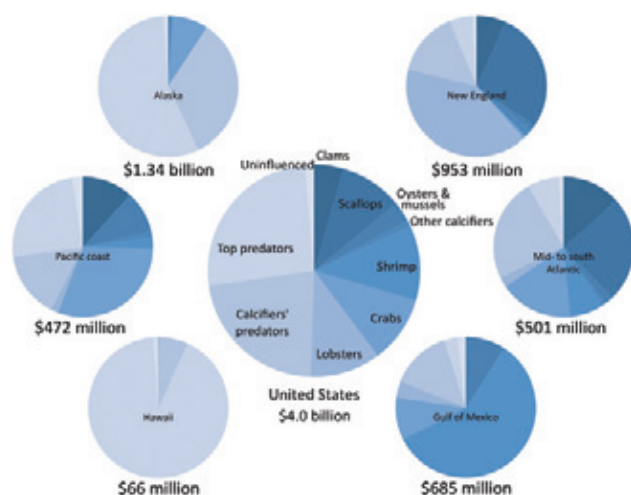


Figure 1. Primary revenue from U.S. commercial fishing (the amount paid to fisherman for the catch, sometimes called ex-vessel revenue) for the U.S. as a whole and broken up by region. Data are for 2006 from National Marine Fisheries Service statistics. The pie charts are divided into groups of species and the darker colors indicate those groups that are directly sensitive to ocean acidification, such as shellfish and crustaceans.

Recreational	Total economic impact (sales, income, jobs)	\$82 billion
	Jobs supported	~530,000
Commercial	Primary sales (the amount paid to fishermen for catch)	\$4 billion
	Retail seafood sales	\$70 billion
	Net contribution to GNP	\$35 billion

Table 1. Revenues from U.S. recreational (Gentner and Steinback 2008) and commercial (NMFS statistics) fishing (US dollars).

AN ECONOMIC ASSESSMENT OF U.S. COMMERCIAL FISHING AND AQUACULTURE

Commercial fishing is a big business today in the United States, and carbonate shell-forming species provide a large portion of its revenues. In 2006, the total value of commercial sales from fishermen to middlemen was \$4.0 billion; shellfish and crustaceans provided 50% of that amount (Figure 1; Andrews et al. 2007). The contribution varies by region around the country (Figure 1); shellfish are more important in the New England and mid- to south Atlantic, crustaceans contribute greatly to New England and Gulf of Mexico fisheries, and predatory finfish (e.g. pollock, salmon, and tuna) dominate the Alaskan, Hawaiian, and Pacific-territory fisheries. Subsequent processing, wholesale, and distribution of all harvests generated retail sales of \$70 billion in 2006, leading to \$35 billion added to the U.S. gross national product that year (Table 1; Cooley and Doney, submitted).

Across the country, the number of jobs generated by U.S. commercial fisheries also grows markedly from catch to retail sale. The total number of jobs in the United States supported by commercial fishing is difficult to constrain, because industry

surveys do not count self-employed fishermen and may not count all middlemen. However, the efforts of a few fishermen support many jobs in seafood processing, transportation, preparation, and sales. Commercial fish processing and wholesaling nationwide supported about 70,000 jobs in 2006.

Recreational fishing also adds economic benefits because recreational fishermen travel, purchase permits and equipment, and patronize supporting industries (Figure 2). This results in the generation of jobs, profits, tax revenues, and business-to-business revenue. In 2006 (the latest date for which data is available), \$24 billion of income, a total impact of \$82 billion from sales and services, and almost 530,000 jobs (Table 1) were created in the United States by recreational saltwater fishing for a total economic impact of \$82 billion that year (Gentner and Steinback 2008).



Figure 2. Saltwater recreational fishing is critical to local and regional economies throughout the United States (SE Alaskan waters pictured). The National Marine Fisheries Service estimates that 25 million saltwater anglers fished 127 million days in the coastal states of the U.S. in 2006.



Figure 3. The American lobster (*Homarus americanus*). Found along the Atlantic coast of North America, American lobsters live a solitary and largely nocturnal existence, feeding on crabs, mollusks, sea urchins, fish, and even macroalgae. Changes associated with ocean acidification may impact lobsters both directly since they use calcium carbonate to form their shells and indirectly through impacts to their food sources.

Growing aquaculture industries worldwide also depend heavily on carbonate-forming organisms like shellfish and crustaceans. In total, 20-25% of the global per capita human consumption of animal protein comes from marine harvests, but patterns of consumption vary widely, and developing and coastal nations often consume high per capita quantities of aquaculture products. In the United States, aquaculture generated \$1 billion of primary sales in 2005 (Andrews et al. 2007), approximately 25% of the value of commercial wild fish harvests. Most aquaculture facilities are located in coastal areas, which will also experience ocean acidification.

	Species	pH	Shell dissolution	Increased mortality	Other
Mussel	<i>M. edulis</i>	7.1	yes	yes	25% decrease in calcification
Oyster	<i>C. gigas</i>	7.1	n/a	n/a	10% decrease in calcification
Giant scallop	<i>P. magellanicus</i>	< 8.0	n/a	n/a	Decrease in fertilization, development
Clam	<i>M. mercenaria</i>	7.0-7.2	yes	yes	
Crab	<i>N. puber</i>	6.0-8.0	yes	n/a	Lack of pH regulation
Sea urchin	<i>S. purpuratus</i>	6.2-7.3	yes	n/a	Lack of pH regulation
Dogfish	<i>S. canicula</i>	7.7	n/a	yes	
Sea bass	<i>D. labrax</i>	7.25	n/a	n/a	Reduced feeding

Table 2. Responses of commercially harvested species to laboratory ocean acidification experiments "n/a"—not available, response is unknown.

DIRECT CONSEQUENCES FOR SHELLFISH AND CRUSTACEANS

Although the full consequences of ocean acidification are not yet known for most commercially valuable species, trends for a few species (determined from laboratory studies) are alarming, indicating that the number and quality of many carbonate shell-forming species may decrease (Table 2; Doney et al. 2009). Because ocean acidification decreases seawater pH and carbonate saturation state, the carbonate shells of many marine plants and animals grow more slowly, or even shrink below certain pH and saturation state thresholds (Figure 3; see Guinotte and Fabry, this issue). The effects of acidification on juvenile marine organisms, however, are largely unknown; if acidification damages juveniles at a key developmental stage, entire populations could be threatened. One cause for concern is that many shellfish grow their juvenile shells from a more soluble form of carbonate and thus may be more susceptible to changes in chemistry. In the worst-case scenario, multiple recruitment failures could cause a population to collapse even if ocean chemistry remains in a range acceptable for adults. In other cases, carbonate-forming organisms that are able to maintain their shells and skeletons in acidified conditions may expend so much energy doing so that their reserves for survival and reproduction may become limited.

Protecting vulnerable marine organisms grown in aquaculture facilities from the effects of ocean acidification may be possible in theory, but it presents practical challenges. Aquaculture is often conducted in tanks or ponds on land that are filled with coastal seawater or within coastal ocean pens. Adjusting seawater chemistry before supplying culture tanks on land would require a great deal of equipment and monitoring that would dramatically increase the overhead of aquaculture

operations. Aquacultured animals in nearshore pens cannot be shielded from ocean acidification.

Laboratory experiments show that oysters and mussels' growth rates decrease and their calcification rates decline by 10% and 25%, respectively, in simulated future ocean conditions when atmospheric $p\text{CO}_2$ reaches 740 ppm, a level that would occur by about 2060 in seawater unless CO_2 emissions are controlled. If decreasing calcification rates observed in the laboratory cause comparable population losses in nature, a 10-25% decrease in all shellfish and crustacean harvests in 2006 would have decreased primary sales from U.S. commercial fisheries by \$200-500 million (Cooley and Doney, submitted). In the future, economic losses will likely vary as marine ecosystems respond and adapt differently to acidification and as economic conditions change. Refining economic loss estimates requires knowing the responses of organisms to ocean acidification, the effects of adaptation or conservation measures enacted in the next 50 years, and the total economic consequences of fishing losses.

INDIRECT CONSEQUENCES FOR FISHERIES AND SOCIETIES

Beyond their direct commercial value, many calcifying species are located at the bottom or middle of the marine food web; therefore, the effects of ocean acidification will likely be transmitted throughout ecosystems by predator-prey relationships (Figure 4; Doney et al. 2009). Nearly all commercially harvested

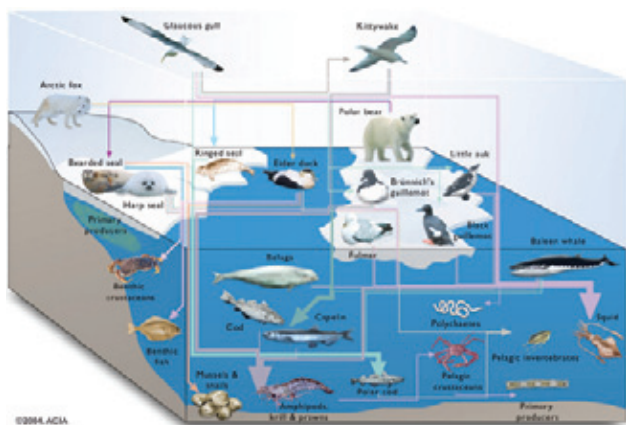


Figure 4. Trophic linkages in the Beaufort Sea. The food web of polar areas such as the Beaufort Sea demonstrates the complex interconnections that are at risk from ocean acidification. Because many Arctic animals depend either directly or indirectly on shellfish for food, reductions in the productivity of these waters due to ocean acidification and changing climatic conditions threaten the base of this and other marine ecosystems.

ECONOMIC IMPACTS OF OCEAN ACIDIFICATION ON LOCAL ECONOMIES

Complicating the estimation of ocean acidification's broader economic effects is the difficulty in quantifying indirect links among marine ecosystems and regional economies. New Bedford, Massachusetts, is an example of a city that could be disproportionately affected by economic losses brought on by ocean acidification (Cooley and Doney, submitted). New Bedford has historically relied on fishing income and currently hosts a large scallop fleet. In 2006, New Bedford had the largest commercial fishing revenues of any single city, about \$280 million in primary sales, almost all from shellfish. This region already has little economic resilience; 20% of its population fell below the poverty line in 1999, approximately twice the statewide (9%) and nationwide (11%) rates that year. In addition, the income gap separating the highest- and lowest-income families is growing at the sixth fastest rate nationwide. Fishery losses in a city like New Bedford could continue to alter its economy and demographics and further accelerate the income gap's development.

wild finfish species prey to some extent on shellfish and crustaceans or their predators. Depletion of calcifying prey would alter or remove traditional food sources and intensify competition among predators for remaining prey species. This indirect pressure would likely reduce harvests of commercially important predators at the same time ocean acidification would directly pressure populations via metabolic or reproductive stress. The overall impact of losing calcifiers on predator numbers is not well known, but the total ecosystem impact of ocean acidification will certainly depend on whether alternative prey species are available and whether predators can switch to prey species that are not affected by acidification.

Coral reef damage associated with ocean acidification will also indirectly pressure marine ecosystems by disrupting the feeding and reproduction of numerous reef-dependent species. Declines in commercially and/or ecologically important species could follow as a result of decreased recruitment or increased success of competitors. In addition to creating unique ecosystems, reefs generate income and economic development from fishing and recreational diving.

If losses of plankton and juvenile shellfish alter marine food webs and losses of coral reefs eliminate habitat, entire ecosystems can shift into entirely new configurations after a sudden disturbance pushes these stressed communities past an ecological "tipping point." This progression is well understood in coral reef ecosystems that have been chronically damaged by temperature or pathogens; ocean acidification is expected to cause similar harm. Continuously stressed reefs become less ecologically resilient, meaning that they are less able to return to a stable, diverse coral community after a disturbance like a storm. Reefs damaged by such short-term events often then become dominated by macroalgae, and species diversity decreases (Hoegh-Guldberg et al. 2007). Herbivores, which tend to be less commercially desirable than predatory reef species, populate the reef. Perturbed ecosystems like these damaged reefs have lower biodiversity, are more susceptible to further injury, and provide fewer ecological services for humans. The mechanisms and outcomes of ecosystem shifts in non-coral reef communities (e.g., estuaries or coastal habitats populated by carbonate-forming organisms) are not as well understood, but non-coral communities may also undergo similar major shifts if plankton and juvenile shellfish losses are significant.

Projecting the economic consequences of ocean acidification's impact on entire ecosystems is difficult because biological responses are not known for most species. We need to understand how finfish populations will respond in the future to possible larval damage, shifts in prey species and distributions, and coral reef habitat loss. Humans play an integral role in shaping marine ecosystems through commercial fishing methods and harvest levels, but the long-term value of these ecosystems depends on more than just the quantity of fish caught in each season. Degraded marine resources affect humans through a variety of environmental connections. Coral

loss will expose low-lying coastline communities and diverse mangrove ecosystems to storm and wave damage, increasing the potential for economic and social disruption following severe weather events. Many coastal and island societies in the developing world depend heavily on marine fisheries and tourism, and they stand to suffer the most economically from the consequences of ocean acidification.

IMPLICATIONS FOR U.S. POLICY AND MANAGEMENT

Until ocean acidification can be mitigated through a global reorganization of the energy and transportation infrastructure, initial responses must target local and regional scales. Action items that would work to maintain sustainable marine resources include: 1) updating fishery management plans to anticipate acidification; 2) adopting ecosystem-based management plans; 3) identifying ecologically resilient areas; and 4) planning for the social and economic consequences of ocean acidification. These efforts do not require large amounts of capital and can be tailored regionally.

Research into ocean acidification's impacts on all life stages (larval, juvenile, adult) of vulnerable marine life is also essential and will allow fisheries to be managed holistically by incorporating species interactions, predator-prey relationships, and the effects of changing ocean chemistry. Fishery management models that include acidification and climate change parameters will help determine appropriate future harvest levels for many fisheries. The likelihood that complex secondary ecological effects will follow species-specific responses emphasizes the need for ecosystem-based management. Ecosystem-scale planning will be particularly useful in areas where fisheries are dominated by predatory finfish (e.g., U.S. Pacific regions). These areas will be particularly vulnerable to changes in keystone/prey species and benthic habitat degradation, which could multiply the net negative effects of acidification.

Implementation of ecosystem-based fishery management and conservation of non-commercial species will allow greater numbers of species to survive changes in ocean chemistry and the ensuing ecological shifts that are likely to occur. A reduction in fishing pressure and preventable environmental stressors (such as local pollution) should begin before ocean acidification's effects on marine resources become obvious. The consequences of a precautionary approach to fishery management could decrease revenues in the short term, but may in fact result in greater fish stocks and higher revenues over the long term. If fisheries are to be sustainable in the face of climate change, then fishery management plans must include indirect impacts on non-commercial prey species and vulnerable benthic habitats.

Finally, changes in fishery management methods in anticipation of ocean acidification can be implemented in a way that balances ecosystem and social objectives by decreasing some catches and increasing others. Catch reductions may require

temporary, regional, or permanent fishery closures in some areas. To maintain economic well-being in marine-resource-dependent communities during such a transition, managers can buy back fishing licenses and gear and provide job training. Increasing fishery capacity might involve encouraging multi-species fishing, developing new markets, minimizing waste, increasing aquaculture, or supporting research to select for species or strains that are less sensitive to altered seawater chemistry (Charles 2007). Mitigating the local economic effects of such a change will require temporary economic support to displaced individuals through re-education and job transitions.

A GLOBAL CHANGE WITH HUMAN CONSEQUENCES

Ocean acidification is a worldwide problem that is poised to affect multiple levels of society through our relationships with the marine environment. Dramatic declines in calcifying organisms and the commercially important species that feed on them are likely to accompany acidification, with substantial direct ecological and economic losses. Less clear are the indirect economic and social consequences of ocean acidification's effects on food webs and marine habitats. Middlemen, retailers, and consumers are all likely to experience secondary losses; the ways in which these groups experience and respond to ocean acidification will partly dictate the total economic and social costs to humans.

Policy changes designed to support marine conservation efforts in the face of ocean acidification must be initiated as soon as possible. Because of time lags in Earth's carbon system, the CO₂ that has already been released will continue to alter ocean chemistry throughout the foreseeable future. Earth has been slow to recover from past perturbations in the carbon system, and the biological changes associated with present-day ocean acidification will become more and more apparent over the coming decades. Economic effects of changing seawater chemistry will compound over time, beginning with losses of single species and culminating in entire ecosystem shifts. Reducing CO₂ emissions over the next few decades, despite the possibility of small up-front costs, could provide noticeable economic benefits over the next several generations.

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RESOURCES

National Marine Fisheries Service commercial fishing statistics: <http://www.st.nmfs.noaa.gov/st1/index.html>

PHOTO CREDITS

Figure and Table 1: Courtesy of Dr. Sarah Cooley

Figure 2: Courtesy of Dr. John Guinotte

Figure 3: Courtesy of NOAA's Undersea Research Program/ Office of Oceanic and Atmospheric Research

Figure 4: Courtesy of Arctic Climate Impacts Assessment (ACIA), *Impacts of a Warming Arctic: Arctic Climate Impact Assessment*. Cambridge University Press, 2007.

Table 2: Adapted from Fabry et al. 2008

THE BIG SEVEN: ACIDIFICATION RISKS AND OPPORTUNITIES FOR THE SEAFOOD INDUSTRY

BY BRAD WARREN

THE SEAFOOD INDUSTRY HAS A STRONG STAKE IN UNDERSTANDING AND confronting ocean acidification. *The Sustainable Fisheries Partnership (SFP), in collaboration with the National Fisheries Conservation Center (NFCC), has developed a program to inform and mobilize fishers, processors, and major seafood buyers to deal with this serious threat.*

As part of this work, we have examined risks and opportunities that this change in seawater chemistry is likely to bring to the seafood industry. A wider examination, considering broader community impacts, would likely yield a longer list. For those involved in the seafood supply chain itself, however, the major risks and opportunities arise in seven areas:

1. Changing productivity.
2. Defining precaution.
3. Knowing enough.
4. Market reactions.
5. Changing investment horizons.
6. Setting CO₂ targets.
7. Shaping carbon strategies.

Each of these seven challenges brings its own risks and opportunities for participants in the seafood industry.

1. Changing productivity. Current scenarios for future CO₂ emissions imply changes in ocean chemistry that are expected to reduce populations of fish and shellfish and to simplify foodwebs. No one knows how much, how fast, or exactly which fisheries will suffer the most rapid losses. Some resilient, harvestable species may gain differential advantages, prompting fishers to shift targets. Worst-case scenarios suggest many commercially-important stocks might collapse, especially if current emissions trends continue to drive toward what some scientists view as a surface-ocean replay of the deep-ocean extinction seen in the hot, acidic Paleocene-Eocene depths about 55 million years ago (Kleypas et al. 2005).

The surface ocean (down to 1,000 meters depth) provides virtually all the world's wild seafood catch (and indirectly, it fuels aquaculture production that depends on feeds made from marine fish). Fisheries that may represent "canaries in the coalmine" include those targeting stocks at high latitudes, resident fish that live in relatively deep and CO₂-rich waters, species found in already carbon-enriched upwelling zones, stocks subject to multiple stresses (e.g. overfishing, thermal change, pollution), and species that cannot tolerate elevated CO₂ concentrations or depend on a prey base or habitats (e.g. some coral reefs) that are particularly vulnerable to this change (Figure 1).



Figure 1. Commercial pink salmon fishing in Alaska. Alaska salmon are among many species in high latitudes that may suffer from possible impacts of ocean acidification to marine food webs. Potential early warning signs are already present, but they are difficult to trace firmly to acidification; other causes are still equally plausible. Last May, Dr. Jeff Koenings, director of the Washington Department of Fish and Wildlife, told a U.S. Senate panel on acidification and climate change that fishery managers have cut harvest rates on West Coast salmon by about two-thirds due to reduced stock productivity. But he and other speakers noted that the cause of this decline are not yet understood.

At first, differential advantages will accrue to fisheries and aquaculture operations that are relatively resilient to elevated CO₂ or less exposed to it (e.g. possibly some tropical fisheries, though this is highly uncertain). Vulnerability of aquaculture is partly due to its dependence on wild feeds. World aquaculture trade relies significantly on carnivorous marine species (e.g. shrimp, salmon, tuna); these and even some herbivorous cultured species are generally raised using feed mixtures that include large volumes of wild fish and fish oils. Some farmed bivalve species are also vulnerable to acidification impacts on calcification and survival.

2. Defining precaution. Some analysts and advocates are recommending that governments curtail catches in an attempt to preserve resiliency of fish stocks in an acidifying ocean. They

are targeting one of the two familiar risks that government fishery managers have always faced: the risk of authorizing too much harvest today, thus squandering abundance, catches, and ecosystem benefits in the future. Fishers frequently concern themselves with the opposite: the risk of squandering today's catch and income by trying too hard to protect tomorrow's.

Acidification widens the bands of uncertainty within which fishery managers must balance their decisions about catch limits (Figure 2). Over time, greater uncertainty is likely to result in decisions that err in both directions—permitting excessive catches in some fisheries, while unnecessarily restricting them in others. Both choices are costly to fishers and those who depend on their catch.

More importantly, acidification also highlights a third familiar risk, and amplifies it: the inadequacy of reducing catches as a tool to counteract rapid, extensive habitat damage. Today, the habitat at risk is the ocean itself.

The challenge of defining precaution in an acidifying ocean will grow as CO₂ concentrations rise and impacts become more severe. Consider these two scenarios:

a) Moderate impact. If acidification elevates “natural” mortality but does not wipe out whole fish populations, scientists and fishery managers may need to rethink biological reference points that are used to manage fisheries. Reduced productivity and resilience in fish stocks due to CO₂, for example, would probably push up the minimum biomass thresholds believed to be capable of quickly regenerating a depleted stock. In acidified waters, a beaten-down fish stock may lose the capacity to recover. This would make precaution in limiting catches even more crucial, but it also suggests that some losses may be inevitable.

b) More severe impact. If acidification threatens to extinguish a harvested stock, overfishing may be viewed (by some lights) as the “best use” of a vanishing resource. This judgment boils down to one question: Is it better to eat the last fish, or let it die “naturally” from effects of CO₂? Much depends here on the level of certainty about a pending loss. If at some point a fish stock faces possible but not certain extinction, fishery managers (and existing U.S. laws) will seek to preserve reproductive capacity, most likely through measures such as refugia and catch restrictions. If extinction looks grimly certain, some managers might consider authorizing an aggressive final harvest. A limited example of this choice occurred in 1913, after a rockslide blocked returning Fraser River salmon from their spawning grounds (Stocker et al. 2008; Isabella 1999).

3. Knowing enough. Acidification brings new urgency to the need to better understand marine ecosystems. This knowledge will be crucial a) to manage fisheries in a changing ocean and b) to drive policies that can protect oceans from increasing CO₂ concentrations. Greater knowledge of a fish stock can permit narrower confidence intervals and more precise “bets” in selecting catch limits that deliver both conservation and economic benefits. The margin of precaution is likely to be greater if impacts of acidification remain poorly understood. This will translate to greater loss of short-term production in fisheries. Thus fishers and seafood companies have an interest in obtaining more precise tools for forecasting impacts of rising CO₂ concentrations on fish stocks. More importantly, they also have a strong long-term interest in research to define the likely future impacts of acidification clearly so that policies and programs can be developed to prevent, slow, or reverse the damage.

4. Market reaction. Acidification could pose both hazards and opportunities for seafood marketers, especially for those

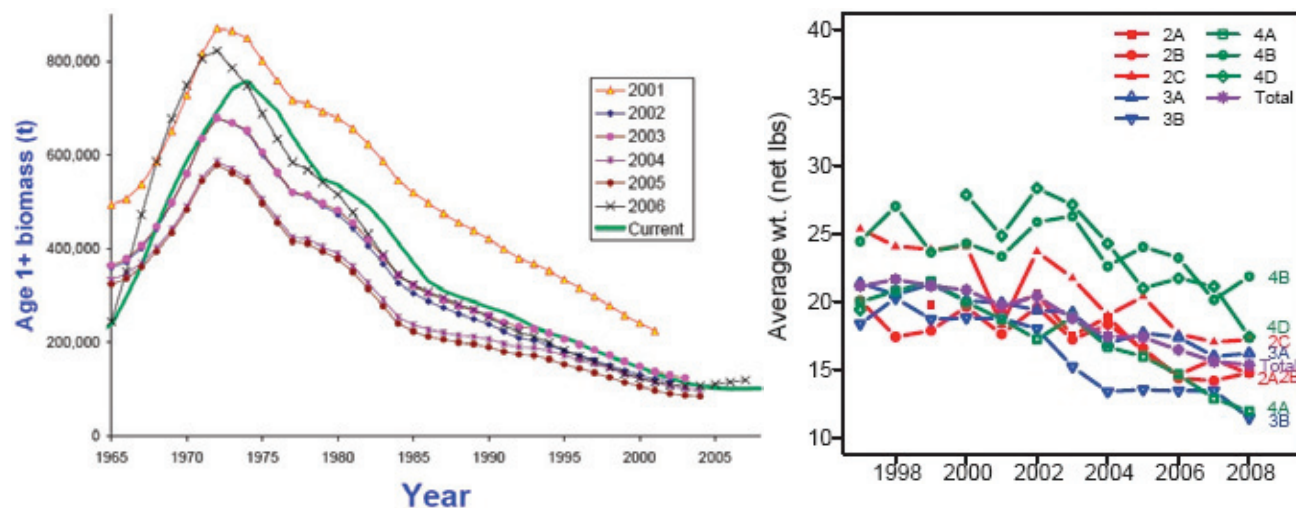


Figure 2. Declining condition of turbot (left) and halibut (right) populations. Declining size at age and poor recruitment in fish stocks are among impacts that can be predicted in an acidifying ocean. Both trends can be seen in many fish stocks around the world today, although little research exists yet to discern whether this is due to acidification or to other factors (especially overfishing). Colored lines on the halibut graph correspond to catches from different management areas.

that have differentiated themselves from competitors through careful, environmentally astute fishery management. Some of the best-managed fisheries in the world are located in vulnerable high-latitude areas (e.g. Alaska, Iceland, CCAMLR Convention waters in the Southern Ocean). However, such fisheries are also unusually well equipped to meet this challenge through research, rigorous conservation measures, and potent advocacy for carbon policies that are strong enough to protect fisheries.

5. Changing investment horizons. Expectations of losses in fishery production due to acidification may either constrain or inspire long-term investments and commitments in the seafood industry. On one hand, acidification raises new questions about the reliability of long-term return on investments in fisheries. This could impede growth or survival of otherwise sound fishing and seafood businesses. In the worst case, this

might encourage some in the fishing industry to forego conservation in order to maximize their most reliable earnings—effectively a “run on the bank” of ocean fish stocks. On the other hand, companies and fishers who work to assure stock conservation and vigorously confront the root problem of excessive emissions could emerge as productive, fuel-efficient, low-cost leaders who wield significant influence in carbon policy. They could claim a role as stewards and guardians of the ocean that feeds us.

Uncertainty about fishery productivity also may affect the cost and accessibility of capital to finance seafood businesses. As lenders and investors begin to factor in acidification risk, differential advantages may emerge.

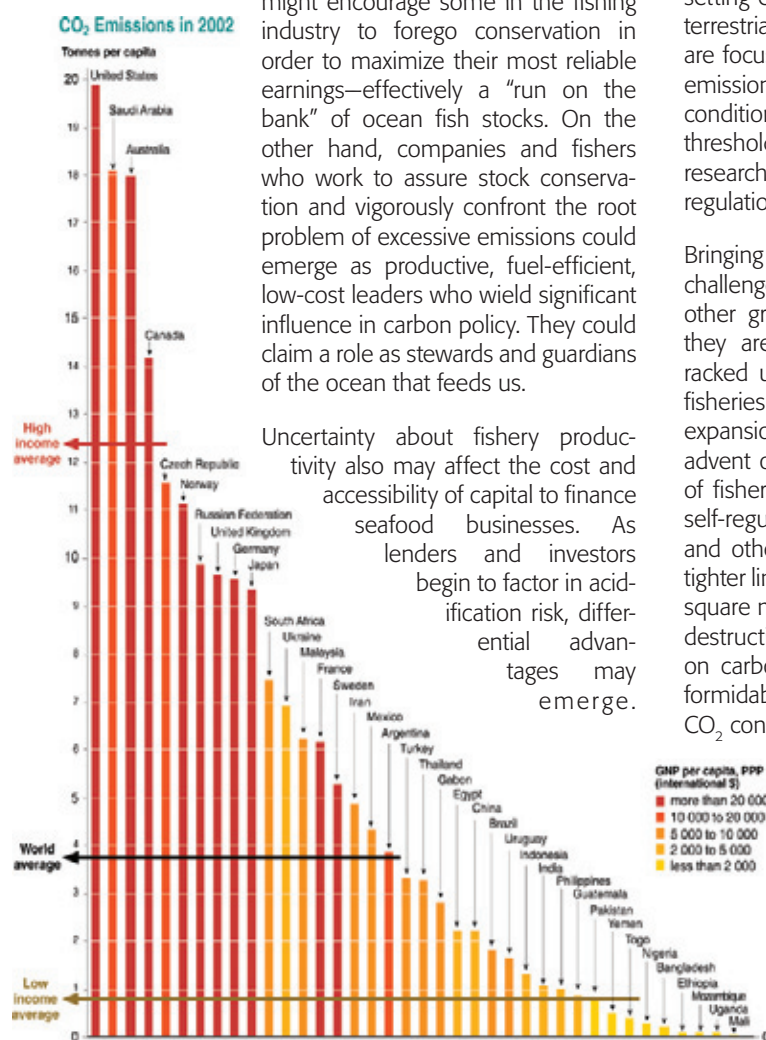


Figure 3. National per capita carbon dioxide (CO₂) emissions. Data on CO₂ emissions by country are difficult to calculate directly and rely heavily on model estimates. While emissions from energy and industrial process are relatively reliable, emissions from agricultural activities carry the highest level of uncertainty. Any attempt to mitigate against the “worst case” scenarios for ocean acidification will require quick action to decrease net CO₂ emissions now and to dramatically reduce the rate of increase for the future.

Producers who can demonstrate resilience to acidification impacts (e.g. through effective stock conservation measures, resilience to acidification, etc.) conceivably could enjoy cheaper borrowing costs or retain greater access to long-term capital than more vulnerable competitors.

6. Setting CO₂ targets. Arguably the biggest risk of acidification for the seafood industry—and for the 1 billion+ people who depend on the oceans for much of their protein—is the chance that societies and governments may neglect to confront the root problem (Figure 3). Failure to pursue ambitious targets for emissions and atmospheric CO₂ concentration would arguably be a disaster for fisheries.

There is a subtler (and specifically marine) variant of this hazard: governments may neglect to consider ocean productivity when setting emissions targets. The climate debate is dominated by terrestrial concerns, and the metrics that guide most decisions are focused on thermal impacts of greenhouse gases. But will emissions reductions that meet thermal objectives for terrestrial conditions also protect the productivity of fisheries? Until CO₂ thresholds for fishery productivity are more clearly defined by research, it will be difficult for policymakers to craft and defend regulations designed to protect it.

Bringing the ocean into climate policy represents an emerging challenge (and opportunity) for the seafood industry and other groups interested in marine conservation. Fortunately, they are skillful advocates. The U.S. seafood industry has racked up remarkable federal legislative “wins” in ocean and fisheries policy since the 1960s. The list includes successive expansions of national fishery jurisdiction culminating in the advent of 200-mile exclusive fishing zones in 1976, a system of fishery management councils that permit a rare degree of self-regulation, special tax benefits for fishing vessel owners, and other measures. Conservationists, meanwhile, have won tighter limits on overfishing, closure of hundreds of thousands of square miles of marine habitat, and rules prohibiting potentially destructive fishing gear in many areas. If they forge an alliance on carbon policy, these two constituencies could become a formidable force for preserving fishery productivity from rising CO₂ concentrations.

7. Shaping carbon strategies. Once governments and companies embrace emissions targets, the game will be won or lost on implementation. Poorly designed and executed strategies might do little to reduce emissions while imposing unnecessary costs on fisheries, on other industries, and on consumers. On the other hand, carbon strategies that are thoughtfully constructed can (and do) make reducing emissions profitable. For example, Dupont’s efficiency efforts

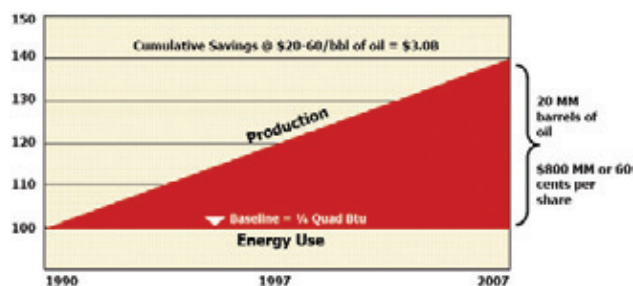


Figure 4. Energy use versus production at Dupont, 1990-2007. Many seafood companies and vessel owners are already evaluating the energy and carbon strategies of other industries to learn how they can reduce fuel costs and cut CO₂ emissions. Dupont, for example, reports that it has saved \$3 billion and reduced greenhouse gas emissions by 72% since 1990, largely by implementing a company-wide program to increase fuel efficiency. In the same period, the company's total production increased by 40%. Dupont's energy consumption, reported as "flat" as of 2007, has since dropped to 6-7% below 1990 levels.

since 1990 have eliminated an estimated \$3 billion in energy costs, reducing total energy consumption by 7% while production from its plants has increased by 40% (Figure 4; Casarino 2008).

Initial design of government carbon policy will determine much about what it costs, who pays, and how rapidly the new system can reduce CO₂ emissions. Carbon emissions markets are likely to deliver more benefits (including better protection for ocean ecosystems and fisheries) if they are open to all. However, at this writing the leading proposals for establishing a U.S. cap-and-trade system would allocate carbon emissions credits only to the biggest emitters (e.g. coal power plants, some heavy industries) and hydrocarbon fuel producers (e.g. coal and oil companies). The seafood industry, and most consumers, would just pay more at the pump.

For fisheries, a system that brings elevated fuel costs and less effective emissions reduction represents a major risk. On the other hand, fishing and conservation interests would gain much from a carbon market that allows everyone to participate. Such a system ideally would reward fuel efficiency improvements, carbon-free power production, and other sources of emissions reduction no matter who delivers them. This would accelerate progress in lowering CO₂ concentrations, create new economic opportunities in trading carbon credits, and generate incentives for emissions reduction at every level of society.

Apart from government policy, companies and NGOs will face a different set of implementation risks as they set out to reduce CO₂ emissions from the seafood industry itself. Not all investments to this end are equally cost-effective. For example, some companies and conservation groups are experimenting with putting carbon footprint labels on retail seafood products. The appeal of this plan is clear: in principle, such labels might permit consumers to choose the lower-carbon option on the grocery shelf or restaurant menu. A strong consumer preference might naturally drive producers to cut emissions.

Unfortunately, two factors make this a costly and unpromising path. First, producing trustworthy carbon labels for food products turns out to be expensive and plagued by uncertainties and assumptions about supply chains. Second, informed consumer choice is a startlingly weak tool for tackling emissions from seafood production, even though it has been a useful lever for curtailing some other fishing problems, such as illegal harvests.

Consumer choice is ineffective here for four reasons:

a) It targets a very small emissions source. The world's fishing fleets produce about 0.2% of global CO₂ emissions, based on calculations from the FAO and EIA data (FAO 2007; EIA 2007). Emissions from the rest of the seafood supply chain appear to be roughly similar in scale, although estimates are less certain. Fishing fleets' share of the global total is so small that even completely eliminating them would fail to protect the ocean from rising CO₂ impacts. All emissions matter, but reducing the total is the real goal, and for this slice of it there are better tools.

b) It can't affect most of the targeted emissions. The high costs and uncertainties of carbon labeling for retail food products mean that only a fraction of all seafood is ever likely to get reliable labels. At best, consumers might be able to compare carbon labels and make informed choices between a few seafood products. Some of these products may indeed show lower carbon intensity than others. However, that marginal advantage, applied against only a sliver of the world's seafood supply, offers precious little "return" (in potential to reduce emissions) for the investment required to produce trustworthy carbon labels.

c) Results are hard to verify. If carbon labels do reduce emissions, this result would be difficult to quantify or confirm. That's because many fishing and processing enterprises are already cutting their fuel consumption for economic reasons, deploying energy-efficiency measures such as thrifter engines and equipment, fuel consumption monitors, and slower cruising speeds.

d) Consumers balk at the bill. The obvious way to pay for carbon labeling is to charge consumers for it. But while surveys persistently show consumers worry about global warming, they also show shoppers don't want to pony up more for low-carbon products (Glynn 2008). It would be doubly hard to justify higher prices for a labeling system that makes little real contribution to emissions reduction.

Indeed, for the seafood industry and other ocean stakeholders, the main risk associated with carbon labels is misallocation of scarce funds to tackle the carbon problem. If they focus too heavily on this tactic, seafood enterprises and conservation groups may miss opportunities to pursue more effective solutions (e.g. reducing global CO₂ concentrations via government policy initiatives and direct investments in energy efficiency).

CONCLUSIONS

The seafood industry has both short-term and long-term interests at stake in the world's carbon crisis, especially because of ocean acidification. Unless oil prices collapse, the industry's short-term need to control fuel expenditures will continue to drive significant investments in energy efficiency, a cost-effective approach. The pursuit of consumer-oriented carbon labels for seafood products represents a risky, costly tactic that could siphon problem-solving resources away from more effective solutions. A thoughtful but aggressive pursuit of efficiency, emissions reduction, and strong carbon policy offers significant opportunities to reduce costs in the short-term, to ensure equal access to carbon markets in the medium-term, and to protect the economic potential of fisheries in the long-term.

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A GLOBAL PERSPECTIVE ON THE ECONOMICS OF OCEAN ACIDIFICATION

BY HAUKE L. KITE-POWELL

THE ACIDIFICATION OF THE OCEANS IS A CONSEQUENCE OF RISING atmospheric CO₂ concentrations and is one of the features of climate change arising from anthropogenic greenhouse gas emissions. The global economic cost of the effect of lower ocean pH on the ability of shellfish, crustaceans, and coral reef organisms to build and maintain their carbonate-based shells is highly uncertain, but could be in the 10s of billions of dollars per year within the next century if carbon emissions continue unchecked. At this level, the effects of ocean acidification will account for a small fraction (likely less than 1%) of the estimated total cost of future climate change; however, it is important to better quantify these ecological and economic impacts, both to inform marine resource management planning and adaptive measures, and to contribute to a more accurate global damage function for climate change and carbon tax policies.

OCEAN ACIDIFICATION—A GLOBAL THREAT TO THE WORLD'S OCEANS

The acidification of the world's oceans is a direct consequence of higher concentrations of CO₂ in the Earth's atmosphere. By absorbing CO₂ from the air, the oceans have taken up between 30% and 50% of post-industrial anthropogenic CO₂ emissions (Sabine et al. 2004; IPCC 2007), which has reduced average ocean surface pH from the preindustrial level of 8.2 to 8.1 (Caldeira and Wickett 2003). Over the next 50 years, rising atmospheric CO₂ is expected to decrease average ocean surface pH to 7.9 or 7.8, and to decrease the saturation states of calcite and aragonite by about 25% (Guinotte and Fabry, this edition).

One of the known consequences of ocean acidification is a slowing or reversal of the growth of the calcium carbonate shells of marine plants and animals, including commercially valuable shellfish and crustaceans and corals. Over time, marine ecosystems will respond to the combined pressures of changes in temperature, pH, and other environmental factors (including fishing effort and anthropogenic pollution inputs) with shifts in the geographic range of species and with other adaptations. This process may include the partial or complete loss of some commercially valuable species.

In this paper, I consider the potential consequences of ocean acidification, and efforts to mitigate these consequences, from a global economic perspective. While we can project the physical consequences of ocean acidification, such as changes in seawater chemistry, with some confidence, anticipating the biological and economic effects is more difficult, because biological organisms (including people) will adapt to changes in ocean chemistry in ways that we may not yet know about. Ocean acidification is a direct consequence of rising atmospheric CO₂ concentration and there is no obvious way to prevent ocean acidification on a large scale, other than to reduce atmospheric CO₂. While ocean acidification and its effects are a rationale for policies to limit



Figure 1. Fisherwoman baiting her shellfish traps, Telukbaku Indonesia. Comprising over 17,000 islands, the Republic of Indonesia and its citizens rely heavily on the oceans for their subsistence and economic welfare. Coastal and marine-related industries comprise approximately 25% of Indonesia's Gross Domestic Product and employ nearly 15% of the country's workforce (Dahuri and Dutton 2000). The importance of these resources will continue to increase; however, the ability of the oceans to provide these services will be mitigated by the effects of local activities (especially destructive fishing practices) and the largescale impacts of climate change and ocean acidification.

CO₂ in the atmosphere, they are best considered as part of the larger set of effects that follow from climate change.

GLOBAL ECONOMIC VALUE OF FISHERIES AND CORAL REEFS

The economic consequences of ocean acidification will depend on the combined adaptations of marine ecosystems and human resource management to the changes outlined above. Although these consequences are difficult to predict, it is possible to say something about the general scale of economic value generated by fisheries and coral reefs, to suggest the order of magnitude of economic value that might be affected by acidification, and to place these values in the broader context of the economics of climate change.

The estimates of economic value I will discuss in the following sections are “order of magnitude” approximations; however, economic losses from ocean acidification, like many other effects of climate change, may well fall disproportionately on relatively poor and under-resourced people; for example, residents of developing countries who depend on reef fisheries or wild shellfish for subsistence (Figure 1). It is a general feature of climate change that the populations most severely affected are often those who have contributed the least, historically, to the problem of carbon emissions. This is an argument for international aid from developed industrial nations to poor countries likely to be hard hit by climate change effects.

Fisheries

Fish provides at least 20% of per capita protein intake for more than 2.6 billion people (FAO 2007). The true significance of seafood to human well-being may well be higher than these figures suggest, because official data do not capture all of the world’s subsistence fisheries. The total economic value generated directly by the initial production of seafood around the world is a combination of capture landings from wild fish populations, and cultured or farmed production from aquaculture operations (Figure 2). Total landed value of world fisheries production is presently around \$150 billion/year. A growing fraction of this, today approaching 50% of all food fish, comes from aquaculture. Table 1 summarizes the contributions of marine and freshwater capture and farming to global fisheries value.

The acidity of the oceans is one important parameter that influences fisheries production; others include ocean temperature, availability of nutrients and other factors affecting primary

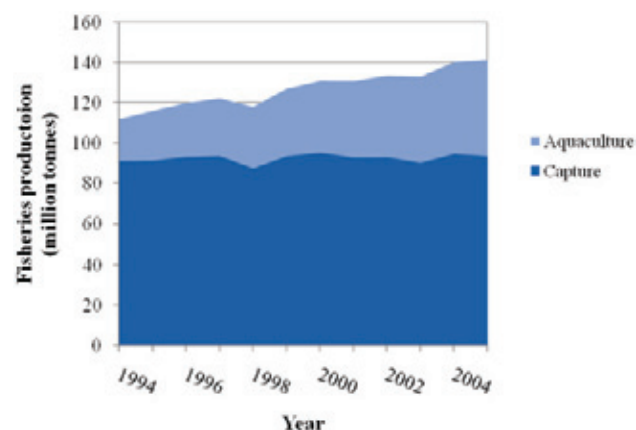


Figure 2. World fisheries and aquaculture production, 1994-2005. Estimates from China are included in these data, although there are indications that production numbers for this country have been overestimated.

productivity, and the state of fish stocks. The state of fish stocks is determined by “natural” factors influencing recruitment and mortality, and also, importantly by fishing pressure, which in turn is determined by fisheries management. While we can say that some fraction of the global economic value of fisheries production is potentially at risk from ocean acidification, it is difficult to anticipate with confidence how the value generated by fishery production will change due to lower ocean pH without also making extensive assumptions about natural and human adaptation to changing ocean chemistry. No models exist at present to provide this kind of projection. Given the declining importance of marine capture fisheries in total global fisheries production, and the potential for ecosystem and human adaptation, it seems reasonable to assume that the direct impacts associated with ocean acidification might eventually impose costs on the order of 10% of marine fishery production, perhaps something on the order of \$10 billion/year.

Coral reefs

Coral reefs cover an estimated 284,300 km² of the world’s oceans (UNEP 2001) and generate economic value primarily as habitat for commercially valuable fish stocks and other types of marine life, as natural protective barriers shielding coastlines from severe waves, and as a source of recreational enjoyment for amateur divers and other coastal tourists (Lewellyn 1998). The full economic value of these reefs has not been estimated in detail, and unit values are likely to vary significantly with

	Wild capture		Aquaculture		Total	
	marine	inland	marine	inland	marine	inland
Production (Mt)	85.8	9.2	18.3	27.2	104.1	36.4
Landed Value (\$ B)	\$84.8 B		\$63.3		\$148.1	

Table 1. Global fisheries production and value for 2004, excluding aquatic plants.

local potential for tourism and the nature and exposure of the shoreline protected by the reef. If we assume that coral reefs generate on the order of \$100,000/km²/year of economic value (a lower bound of a range suggested by Burke and Maidens [2004]), this suggests a global economic value generated by the world's reef on the order of \$30 billion/year (note that there is some overlap between this estimate and the fisheries values described above). A potentially significant fraction of this value is thought to be at risk in the future due to the combined



Figure 3. *Stylophora* coral on blue *Montipora* coral. Warm-water corals are impacted by climate change, including sea surface temperatures, which leads to the expulsion of the zooxanthellae. This phenomenon is known as 'bleaching' and if prolonged, will usually lead to the death of the coral.

stress of water temperature, pollution, and other environmental changes, including ocean acidification (Figure 3). How reefs will respond to these stresses in the long run is not well understood, and no model exists to parse the contribution of ocean acidification from the aggregate environmental pressures to which reefs are exposed.

Coral reefs are known to be affected significantly by changes in water temperature (UNEP 2001), and illustrate perhaps more clearly than fisheries the need to consider stress from ocean acidification in the broader context of climate change effects. There is much uncertainty around the estimates suggested

above, but it seems plausible that, within the next century, ocean acidification could be a significant contributing factor to economic losses in the 10s of billions of dollars per year from its effects on fish populations and coral reefs.

COSTS OF MITIGATION

Efforts to mitigate the effects of ocean acidification can take two general forms: adaptation, which accepts lower pH levels in the oceans and adjusts economic activity and resource management to take this into account; and remediation, which seeks to restore ocean pH levels to something approximating preindustrial levels so as to avoid the negative effects altogether.

It may be possible to influence local and regional ocean pH through geo-engineering schemes over limited periods of time; but this has not been demonstrated and could carry with it costly ecological side effects. If marine conditions become unfavorable for commercially valuable fish species in their present habitat, fish farmers may choose to switch to controlled production environments in onshore tanks or ponds, or to take measures to control pH at a local scale in the marine environment around the fish farm. This form of adaptation is costly—the preferred way to farm marine species today involves the use of cages or shellfish beds in the ocean—but some fish are already commercially grown in onshore facilities today.

It is not clear to what extent it may be possible to mitigate the effect of ocean acidification on coral reefs or across large ecosystems. Broadly, remediation on global scales at present appears possible only by reducing atmospheric CO₂ concentrations to levels that are compatible with a surface-ocean pH around 8.2. Most of the schemes for reducing atmospheric CO₂ involve the capture of carbon, either directly at the source (exhaust from

CARBON TAX

Economists refer to taxation on emissions of carbon dioxide and other greenhouse gases as a "carbon tax," which is easily implemented (in theory) by taxing the sale of fossil fuels. Revenue from the tax can then be used to pay for investments in alternative energy and other climate change mitigation efforts. In practice, the carbon tax is complicated because taxes are generally unpopular, and because such a tax would have to be agreed upon and implemented by all major greenhouse gas emitting nations. It has estimated that an optimal global climate policy would impose an effective carbon tax of \$30-50/ton at present, and increase this tax to about \$200/ton carbon by the end of the century (Nordhaus 2007). At \$40/ton, such a tax would increase the annual electric bill of a U.S. household whose electricity comes from coal-fired power plants by about 10%.

fossil fuel combustion), using an absorbing medium, or from the air into plant matter via photosynthesis, and the long-term sequestration of that carbon to keep it from re-entering the atmosphere. Fossil fuel combustion alone releases more than 6 billion metric tons of carbon into the atmosphere each year; and the cost of carbon capture is around \$150/ton. A significant reduction in atmospheric CO₂ will be expensive to achieve. How much is the world willing to spend to do this?

THE GLOBAL CONTEXT OF CLIMATE POLICY

From an economic point of view, the optimal response to the prospect of climate change caused by anthropogenic emission of greenhouse gases has to trade off expected future damages caused by climate change against the cost of measures taken now and in the future to reduce that change. If we know that the future cost imposed by climate change is likely to be high, we are justified in spending more money today to reduce carbon emissions than we would if future costs of climate change were likely to be low.

The future cost of climate change is measured by economists as a reduction in global economic output, something akin to a combined Gross Domestic Product of all the world's nations. For example, recent estimates of the damages likely to arise from global warming are on the order of 5% of global economic output for a 4°C increase in mean global temperature (IPCC 2007; Nordhaus 2007). That level of damage justifies significant investment in present and future efforts to slow the increase in, and eventually to reduce, the concentration of CO₂ and other greenhouse gases in the Earth's atmosphere. If we know (1) the

loss the world is likely to suffer from a given increase in temperature, (2) how temperature varies with CO₂ concentration, and (3) how each ton of carbon we emit to the atmosphere contributes to future CO₂ concentration, we can estimate the future damage that can be ascribed to each ton of carbon we emit today.¹ We can then encourage individuals and corporations to reduce how much carbon they emit by charging them for each ton of carbon they release (i.e., a carbon tax).

The optimal carbon tax depends in part on the "damage function," the relationship between the concentration of CO₂ and other greenhouse gases in the atmosphere, and the economic losses imposed on the global economy by changes in climate. Estimating this damage function requires making numerous assumptions about future population levels, economic activity, and technological change; it must deal with a lot of uncertainty. Present models are far from perfect, but they are a useful start, and there is much ongoing work dedicated to refining them. The economic costs imposed by ocean acidification appear to be a small component of the total cost of climate change: five percent of global economic output represents at present about \$3 trillion and even a "generous" projection of the implications of ocean acidification is unlikely to produce future costs larger than about 1% of this amount. As noted above, however, these aggregate global numbers do not reflect serious issues concerning how the costs are distributed across different regions and populations (Figure 4). These distributional issues are most effectively addressed by separate international aid agreements that should accompany the global carbon tax policy.

Although it is a minor component of the total cost of climate change, it is important to understand the implications of ocean acidification. Because the damage function remains one of the major sources of uncertainty in efforts to model the economics of climate policy (Nordhaus 2007), research on the likely physical, biological, and economic effects of ocean acidification can help inform this work by reducing uncertainty about one component of the total damage function. It is the estimate of expected total damage in future years that should drive carbon tax and climate policy, since all components of these damages, including those due to ocean acidification, are ultimately driven by the common forcing of atmospheric CO₂ and other greenhouse gases.

CONCLUSIONS

Even under an economically optimal climate policy, atmospheric CO₂ levels will continue to rise, for several decades and possibly for more than a century. This means that even under an economically sensible scenario, in which the world can agree sufficiently on a common climate policy (carbon tax) to follow a reasonable path of carbon emissions reduction, the oceans are likely to face atmospheric CO₂ levels in the 700-800 ppm range—but in the 22nd century, not the 21st as the IPCC projections (2007) suggest they would without emission reductions



Figure 4. Pike Place Market, Seattle Washington. The economic value of fisheries varies regionally throughout the world. In the state of Washington (U.S.), shellfish and marine fisheries are strong contributors to the state's economy. In the year 2000, for example, Washington was the leading producer of farmed bivalve shellfish in the U.S., generating approximately \$77 million in sales annually. In these areas, the impacts of ocean acidification could be substantial, yet comprehensive risk assessments have not been undertaken in Washington.

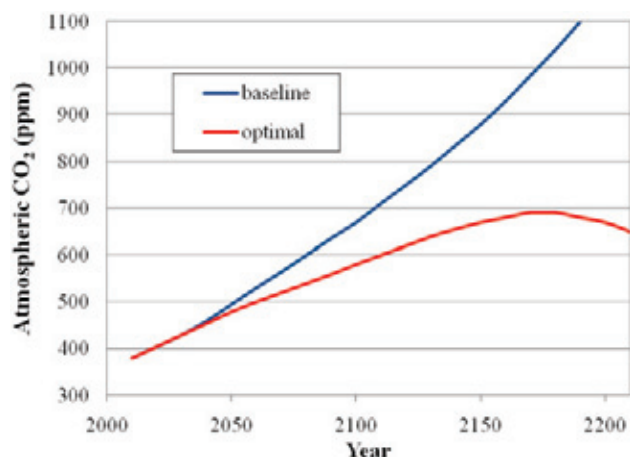


Figure 5. Projected rise in atmospheric carbon dioxide concentrations under two different carbon policy scenarios. Without serious steps to reduce carbon emissions, the concentration of CO_2 in earth's atmosphere is projected to rise at an accelerating rate (baseline, blue). An economically optimal global carbon tax would reduce carbon emissions, resulting in a slower rate of increase and, eventually, a decline in carbon concentration (optimal, red). This policy would delay reaching 700 ppm from this century to the next, buying more time for adaptation and mitigation.

(Figure 5). This implies that marine ecosystems will eventually have to contend with pH levels in the 7.8 to 7.9 range even with significant global carbon management measures. A sensible carbon policy would ensure that things do not get worse than this and that we buy the world's ecosystems, and ourselves, more time to adapt and respond.

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ENDNOTE

¹ In practice, this is complicated by the challenge of trading off the wealth of the present world population (many of whom are relatively poor) against the wealth of future generations (who, if the past is a guide, may be much better off on average). It turns out that the choice of the discount rate, by which future wealth is related to present wealth, is a critically important factor in these calculations—see Nordhaus (2008) for a thorough explanation.

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Figure 5: Courtesy of Nordhaus (2007)

WHAT CAN BE DONE TO ADDRESS OCEAN ACIDIFICATION THROUGH U.S. POLICY AND GOVERNANCE?

BY EDWARD L. MILES AND JAMES BRADBURY

THIS PAPER WILL FIRST ASSESS THE PROBLEM OF OCEAN ACIDIFICATION

as a policy problem which is unique in its constellation. Consequently, the focus will be on the following dimensions: what policymakers and the general public need to know about the problem; what types of responses are possible in the face of the challenges that are presented; and what kinds of capacity building would seem to make most sense.

Following this assessment, we will outline the initial approaches to defining both policy and governance, which are in motion within the U.S. Congress.

WHAT KIND OF POLICY PROBLEM IS OCEAN ACIDIFICATION?

Ocean acidification (OA) is the consequence of rising anthropogenic emissions of CO₂ since 1750, and the uptake of between 30 to 40% of that carbon by the ocean (Kleypas et al. 2006; Zeebe et al. 2008; Doney et al. 2008). The emergence of OA is not an impact of changing climate like increases in average global temperature, increased melting of sea ice, or increasing intensity of hurricanes and tropical cyclones. The acidification is the direct result of the uptake of human emissions of CO₂, which change ocean chemistry by reducing pH. Consequently, there are three critical elements of ocean acidification that make it a unique policy issue:

1. The high level of **certainty** regarding acidification;
2. The timescale of responsiveness which is determined by the rate at which the ocean takes up CO₂ from the atmosphere, and the rate at which the water in the large ocean

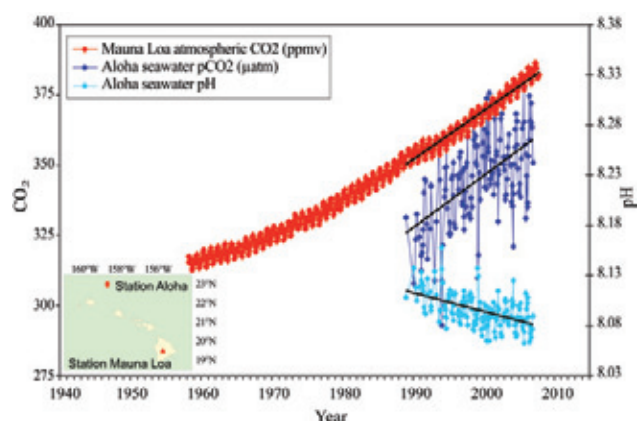


Figure 1. Time series for atmospheric CO₂ and seawater pH at Mauna Loa. One of the most compelling series of observations of changing atmospheric CO₂ concentrations is from the Mauna Loa volcano observatory on the big island of Hawaii. This graph shows measurements of atmospheric CO₂ (red data points) that date back to the 1960s, in addition to the partial pressure of CO₂ in seawater (dark blue data points) and decreases in pH (light blue data points) from this area.

FIVE CRITICAL FACTS

1. Global climate is changing as a result of the anthropogenic input of CO₂ since the beginning of the industrial revolution in the mid-nineteenth century (Figure 1).
2. Current atmospheric concentration of CO₂ (383.7 parts per million by volume [ppmv]) is greater than the natural range of 180 to 300 ppmv for at least the last 650,000 years (IPCC 2007 AR4.2007. WGI, SPM).
3. The current rate of atmospheric CO₂ increase for the last decade has now exceeded the rate observed over the period 1958 to 1998 (Raupach et al. 2007). So what is likely to happen in the future will be more severe than the IPCC's "business as usual" scenarios which have been the standard for the worst case.
4. We need to reduce emissions to address this problem, and the most important policy act is to facilitate global agreements for implementing severe cuts in human CO₂ emissions.
5. Climate, in the form of increasing temperature, impacts marine ecosystems primarily from the bottom up (i.e., at the lowest trophic level), and so does acidification.

This combination of drivers is powerful enough to change entire marine ecosystems on a regional spatial scale and perhaps on decadal timescales.

basins turns over bringing with it the dissolved inorganic carbon (DIC) from the depths. These rates vary from decadal to millennial timescales. The result is that we cannot reverse the levels of acidification to which the world ocean is already committed, even though those levels are as yet unrealized, but we can prevent the trends from increasing indefinitely; and

3. The fact that ocean acidification is an additional major stressor to ocean ecosystems, and one which acts to varying degrees over the entire world ocean.

WHAT THEN CAN WE DO TO RESPOND TO THE CHALLENGES WE FACE?

In addition to mitigation, we can identify four elements of an effective policy response:

1. **Research**, to augment our database, since our knowledge of acidification and the quantitative effects of multiple stresses is thin.
2. **Monitoring**, to keep abreast of changes in the open and coastal ocean. The stark surprises in the findings of Feely et al. 2008, demonstrating a shoaling of aragonite under-saturated water in the coastal ocean of the N.E. Pacific indicates we are far behind the curve of change (Figure 2).
3. **Ecosystem-based fisheries management (EBM)**, to allow us to manage entire marine ecosystems. Our ap-



Figure 2. New buoy to monitor ocean acidification. Measurements of seawater pH have been collected for decades primarily through ship-based water sampling. Only in 2007, however, did the U.S. launch its first buoy dedicated to measuring ocean pH. Located at the Ocean Station Papa (50°N, 145°W) in the Gulf of Alaska, this 10-foot buoy provides measurements of air-sea exchange of carbon dioxide, oxygen, and nitrogen gas in addition to measuring the pH of surface waters. Scientists hope that this sensor will provide critical data on the progression of ocean acidification and in a region of the ocean that will be extremely vulnerable to declining pH.

proach to EBM must be place-based, flexible, and adaptive to changing conditions, constantly seeking to balance short-term and long-term objectives.

4. **Understanding where changes are occurring on variable timescales**, which create or enhance vulnerabilities of place-based coupled social-ecological systems. Adopt risk-averse policies to remove or limit threats.

INITIAL APPROACHES TO POLICY AND GOVERNANCE IN THE U.S. CONGRESS

To U.S. policymakers currently focused on solutions to global warming, the issue of ocean acidification adds another important reason why fast policy actions are necessary to abate CO₂ emissions, protect our economy, and preserve the health of our global ecosystems. With rising sea levels, shrinking glaciers, and sea-ice disappearing rapidly in the Arctic, a sense of urgency is already palpable to many policymakers, particularly those committed to achieving "stabilization of greenhouse gas concentrations in the atmosphere at a low enough level to prevent dangerous anthropogenic interference with the climate system (UNFCCC, 1992)."

On the research side, in the 109th Congress, Rep. Jay Inslee (D-WA) successfully passed an amendment to the Magnuson-Stevens reauthorization bill requiring that the National Research Council study the effects of ocean acidification; however, without Congressional appropriations, this will remain an unfunded request. The 110th Congress made significant progress toward passing into law a comprehensive bill (the Federal Ocean Acidification Research and Monitoring Act; the FOARAM Act) that would authorize greater funding levels and establish a more coordinated national effort to research, monitor, model, and assess the impacts of ocean acidification. Due to a combination of unfortunate timing and unfavorable election-year politics, this bill never passed in the 110th Congress.

THE LEGISLATIVE PROCESS FOR THE FOARAM ACT

Senator Frank Lautenberg (D-NJ), introduced with Senator Maria Cantwell (D-WA), in June, 2007, S. 1581 (the FOARAM Act), a few weeks after the Senate Subcommittee on Oceans, Atmosphere, Fisheries, and Coast Guard held a hearing on the effects of climate change and ocean acidification on living marine resources. The bill subsequently earned bipartisan support and passed by voice vote out of the Committee on Commerce, Science, and Transportation in December 2007.

In November 2007, Rep. Tom Allen (D-ME) introduced with bipartisan support the House companion to the FOARAM Act (H.R. 4174). In June 2008, the bill moved quickly through committee and to the Floor, where it passed by voice vote on July 9th. Through this process, the House Committee on Science and Technology gave the FOARAM Act significant vetting, beginning with a hearing on June 5th in the Subcommittee on Energy and Environment. Testifying at the June hearing was a panel of expert witnesses.

To reflect recommendations made in the hearing, Rep. Brian Baird (D-WA) and Rep. Bob Inglis (R-SC) together with the Committee on Science and Technology produced the amended version of H.R. 4174 that later passed on the House Floor. The bill would establish an Executive Branch interagency program, coordinated by the Joint Subcommittee on Ocean Science and Technology (JSOST), to develop and manage a comprehensive plan to better understand and address ocean acidification issues. The program would provide for assessment of ecosystem and socioeconomic impacts, monitor and model chemical and biological changes, research adaptation strategies to conserve marine ecosystems, and technology development for improved carbonate chemistry measurements. The bill would also require JSOST to actively involve a broad range of ocean community stakeholders in the development of the plan, including universities, states, industry, and environmental groups. Finally, the bill would authorize ocean acidification activities at the National Science Foundation and the National Aeronautics and Space Administration and authorize funding for these activities over a four-year period.

Despite having cleared most other hurdles to final passage, legislative progress in 2008 on FOARAM stalled in the Senate when U.S. Senator Tom Coburn (R-OK) put a "hold" on S. 1581, along with a raft of other bills that would increase authorized government spending levels. Putting bills on hold prevents Senate leadership from expediting their passage by requiring first that they be subject to debate and votes on the Senate Floor. Since Senate Floor time is a premium commodity, the act of placing a bill on hold is practically tantamount to killing it, especially in the final days of a legislative year. A partisan debate over energy policy in the summer and a financial crisis in the fall prevented any other legislative progress in 2008.

NEXT STEPS

Public outreach and education efforts could be increased so that Americans better understand the link between global warming and ocean acidification. For example, in May 2008, Senator Cantwell held a Congressional field hearing in Washington State to examine the impacts of climate change on ocean and coastal ecosystems in the region. Witnesses testified on the effects of climate change and ocean acidification on marine ecosystems in Puget Sound and coastal Washington, including the economic impacts on coastal communities.

The development and legislative progress of the FOARAM Act represents a significant step forward for federal ocean research, policy, and governance. Environmental policy leaders in the House and Senate will likely take it up again early in the 111th Congress. Once passed and signed into law, additional funding plus the process of establishing a plan for research, monitoring, and impacts assessment will further engage a variety of national and international stakeholders, particularly the fishing industry and coastal communities, who have a significant economic stake in sustainable ocean ecosystem management.

Though the issue of ocean acidification has come somewhat late to the climate policy debate, most energy and land-use policy solutions are well suited to addressing both global warming and ocean acidification. Thus, further research into the ocean acidification phenomenon will help inform policy decisions regarding the mitigation and adaptation solutions to this and other climate change impacts. Meanwhile, efforts to reduce greenhouse gas emissions through meaningful national and international policy action will remain an urgent matter, if we are to prevent catastrophic climate change and the most severe consequences of ocean acidification.

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Figure 1: Data and Graph Courtesy of Dr. Richard A. Feely

Figure 2: Courtesy of NOAA

RESILIENT CORAL REEF ECOSYSTEMS PROVIDE A GLIMMER OF HOPE FOR THE FUTURE

BY JENNIFER SMITH, ELIZABETH RAUER, AND LARISSA SANO

TROPICAL CORAL REEF ECOSYSTEMS ARE SOME OF THE OLDEST KNOWN

ecosystems on Earth and house some of the greatest biological diversity of any ecosystem in the world. Due to a range of human activities, however, these ecosystems are now imperiled. Over the past several decades, hundreds of scientific reports have documented the declining condition of coral reef ecosystems in areas ranging from the Caribbean (Gardner et al. 2003) to Indonesia (Edinger et al. 1998) and the Pacific (Brunoe et al. 2007). A recent report by Carpenter et al. 2008 estimates that more than one-third of all reef-building corals in the world now face the risk of extinction. Given the numerous challenges already facing warm-water coral reef ecosystems (see inset: The Threats to Corals), ocean acidification threatens to be the proverbial “straw that broke the camel’s back.”

THE THREATS TO CORALS

Around the world, warm-water coral reef ecosystems are increasingly threatened by both large-scale changes in ocean conditions and by more localized threats. Globally, declines in coral health are driven by coral bleaching and disease, both of which are associated with increasing sea surface temperatures. Locally, human activities such as overfishing, sediment and nutrient runoff (including fertilizers and sewage) from upland development, and coral harvesting for the aquarium trade further harm the health of coral reef ecosystems.

The few remaining healthy warm-water reefs harbor important clues about how healthy coral reefs respond to changing ocean conditions. One exceptional site for coral reef studies is the Line Islands, located in the remote warm waters of the tropical Pacific Ocean. Extending approximately 1,200 miles north-south, the Line Islands are comprised of a group of low-lying sparsely populated or uninhabited coral islands, atolls, and reefs (Figure 1). Three of the islands are unincorporated territories of the United States, while the remaining eight are part of the Republic of Kiribati.

Recently an expedition to the northern Line Islands led by researchers from Scripps Institution of Oceanography sought to determine the effects of human activities on coral reef health. A team of researchers spent 40 days at sea aboard a 130-foot decommissioned World War II navy ship. During this time, scientists collected data on coral, seaweed, and fish abundance, as well as coral disease, microbial and viral abundances, and the physical and chemical properties of the seawater. The results from this study yielded clear patterns of coral reef health: where

there were more people and higher fishing pressure there were fewer fish on the reefs and less live coral. Perhaps the most important finding, however, was that islands with little to no human impacts demonstrated greater ecological resilience and were thus able to recover more quickly from extreme ocean conditions than those reefs with human inhabitants (see Sandin et al. 2008 for additional details).

KINGMAN AND KIRITIMATI—A TALE OF TWO ATOLLS

Kingman atoll occupies the northernmost site in the Line Islands. It is an uninhabited coral reef, only one square mile in size and is currently protected by the U.S. Fish and Wildlife Service. Kiritimati (also known as Christmas Island), in comparison, is the largest of all Line Islands, encompassing 124 square miles and supporting approximately 5,000 human inhabitants.

These atolls have striking differences in their coral reef communities: Kingman atoll is covered with healthy stone corals and crust-forming red algae (i.e., crustose coralline algae), both important reef builders (Figure 2 A, B). Small new coral recruits are abundant at the site, indicating a thriving coral community. Large seaweeds which are often strong competitors of corals

ATOLLS

Atolls are circular islands that enclose shallow water lagoons. They form when volcanic ocean islands with a fringing barrier reef sink below sea level. This geology of atoll formation was first hypothesized by Charles Darwin, one of his lesser-known discoveries he made while aboard the *Beagle*. Atolls are mostly found in the tropics and subtropics of the Pacific and Indian Oceans.

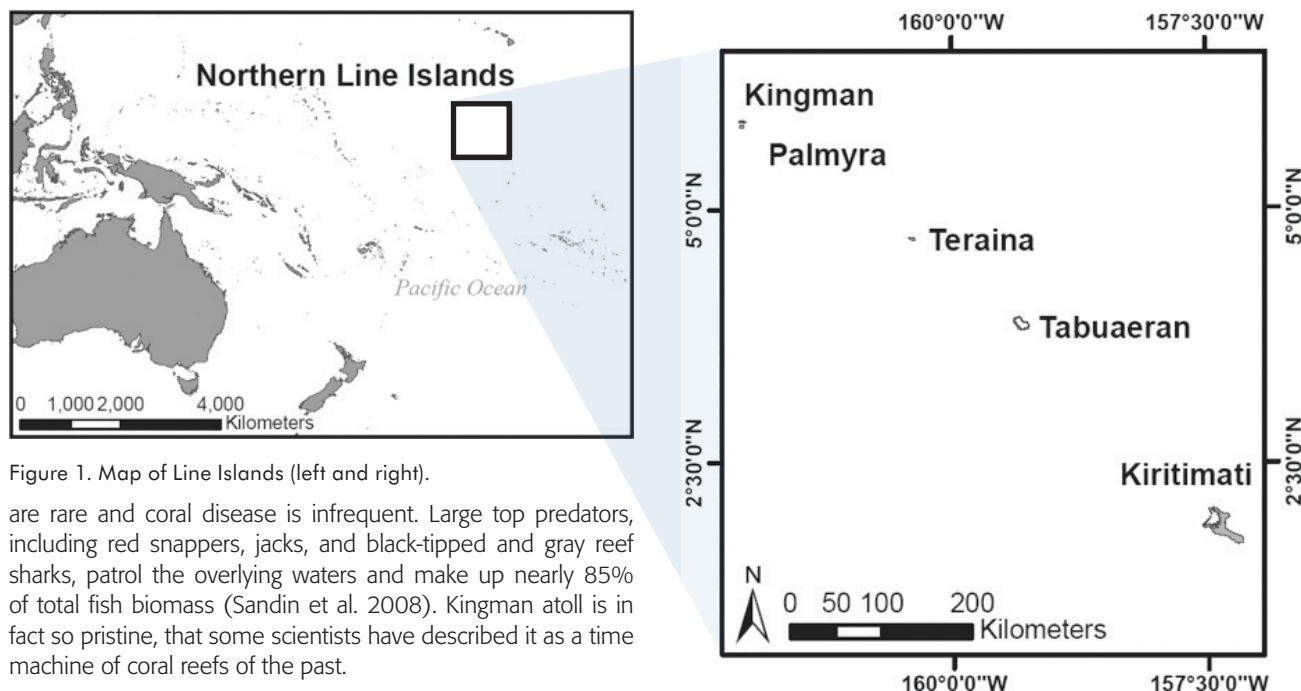


Figure 1. Map of Line Islands (left and right).

are rare and coral disease is infrequent. Large top predators, including red snappers, jacks, and black-tipped and gray reef sharks, patrol the overlying waters and make up nearly 85% of total fish biomass (Sandin et al. 2008). Kingman atoll is in fact so pristine, that some scientists have described it as a time machine of coral reefs of the past.

Kiritimati, in contrast, has few top predators and almost no sharks. Small plankton-eating fish, such as damselfish, instead account for more than one-fourth of the total fish biomass there (Figure 2 C, D). Kiritimati is also dominated by extensive mats of algae (macroalgae or seaweeds) and has far fewer stony corals and less crustose coralline algae than Kingman. Commercial fishing operations for both food and aquarium fish operate in Kiritimati's waters. In 2005 alone, 161,500 aquarium fish were removed from Kiritimati, primarily angelfish (from Sandin et al. 2008).

In addition to the differences described above, there are other factors that might contribute to variations in coral reef health between these two sites. Kingman is located further north and thus tends to experience lower sea surface temperatures than Kiritimati. The waters around Kiritimati also experience stronger upwelling events, which bring cold-nutrient-laden deep waters to the surface (Sandin et al. 2008).

HUMAN ACTIVITIES—THE MAIN DRIVER OF CHANGE

Despite these differences, historical evidence from Kiritimati suggests that human activities, specifically fishing, are the primary driver of coral reef decline. A study as recently as 1997, for example, reported that top predators constituted 30% of the total fish biomass in Kiritimati (Sandin et al. 2008). The sharp decline in this trophic level is consistent with over-fishing, which preferentially reduces the density of longer-lived, larger-bodied individuals (Myers and Worm 2003).

The disproportionate impact of fishing at Kiritimati is further supported by studies from uninhabited coral reefs located further south: the uninhabited and protected atolls of Jarvis,

Howland, and Baker support abundant populations of top predators and have healthy coral reefs, comparable to those described at Kingman (Brainard et al. 2005; Sandin et al. 2008), yet are located in the center of the equatorial counter current which causes even more extreme temperature variations than found at Kiritimati. This apparent resilience of these healthy reefs gives hope that sustainable local management practices can increase the ability of coral reefs to recover from the global stresses associated with climate change.

THE FUTURE HEALTH OF CORAL REEFS—RESTS IN EVERYONE'S HANDS

The future of tropical coral reef ecosystems rests in everyone's hands. While the international community needs to act quickly to reduce global CO₂ emissions, there is much that individual governments, communities, and local citizens can do to help preserve coral reef ecosystems.

Five things you can do to help:

1. Reduce your ecological footprint—drive less, use less energy and water, buy locally-grown food, recycle, buy less, and appreciate more of what you already have. Although these things sound simple, if the approximately 305 million people in the U.S. did these things more often, the collective impact and environmental benefit would be substantial. Now imagine what we could accomplish if everyone in the world (more than six billion people) also joined in.
2. Write to your local and national representatives and let them know coral reefs, large predatory fish, and ocean

ecosystems are in danger—and that you value ocean ecosystems—and ask them to make it a priority to protect these important places.

3. Be an ocean-conscious consumer. Avoid purchasing live coral and reef fishes that were taken from the wild—some of which are collected using dynamite and cyanide that harm living reefs. When buying seafood, purchase sustainable seafood.
4. Support environmental organizations that work to protect our natural environment, get involved with their activities.

5. Spread the word. Inspire your friends and family to help protect these beautiful places, and let them know what they can do to help.

For more information and additional ideas and activities, please visit:

NOAA's 25 things to save corals:

www.publicaffairs.noaa.gov/25list.html

The Nature Conservancy's footprint calculator:

www.nature.org/initiatives/climatechange/calculator/

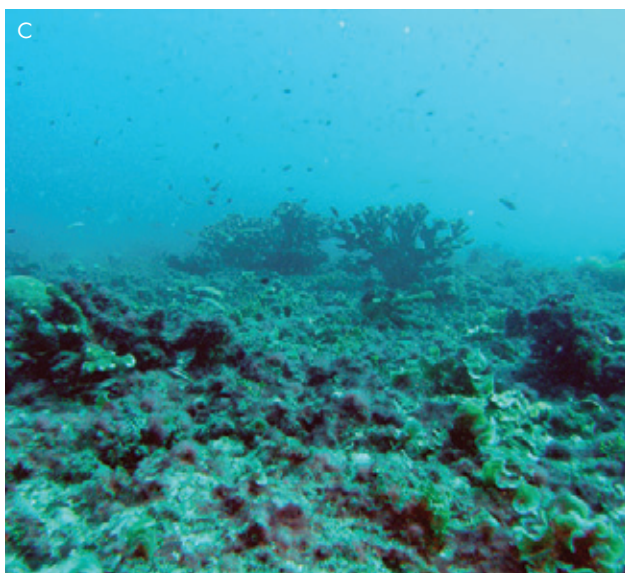


Figure 2. Kingman reef (A, B) is characterized by abundant and healthy corals and supports a high biomass of top predators such as gray reef sharks, while Kiritimati (C, D) is dominated by seaweeds and supports mostly small planktivorous fish species.

Monterey Bay Aquarium's seafood watch card:

www.mbayaq.org/cr/cr_seafoodwatch/download.aspx

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PHOTO CREDITS

Figure 1: Courtesy of Lisa Wedding, University of Hawaii, Manoa

Figure 2: Courtesy of Dr. Jennifer E. Smith

Page 36: Courtesy of Dr. Enric Sala

THE PACIFIC REMOTE ISLANDS NATIONAL MONUMENT

On January 6th, 2009, President Bush made significant progress in supporting coral reef conservation in U.S. waters by designating three ecologically significant areas in the Pacific Ocean as Marine National Monuments. Combined, these sites encompass approximately 195,000 square miles, and house an immense diversity of marine life. One of these monuments, the Pacific Remote Islands National Monument, includes seven remote island possessions and territories and surrounding waters in the Central Pacific—Wake Island, Johnston Island, Palmyra Island, Kingman Reef, Baker Island, Howland Island, and Jarvis Island. All of these areas will receive the same level of protection as U.S. National Monuments, with a quick phase out of commercial fishing activities and other extractive uses. Because these areas include some of the most pristine tropical islands and coral reef ecosystems in the world, this accomplishment is an essential step in safeguarding these unique ocean places. To find out more about these new national marine monuments visit http://www.mcbi.org/what/national_monuments.html.



ACTIVITY: DEEPWATER CORAL EXPEDITION: REEFS, RIGS, AND WRECKS



THE FOLLOWING LESSON FOCUSES ON PH, BUFFERS, AND OCEAN acidification and was developed to complement the science behind the—*Lophelia II 2008: Deepwater Coral Expedition: Reefs, Rigs, and Wrecks*—which is sponsored by the National Oceanic and Atmospheric Administration's Ocean Exploration and Research Program and the Mineral Management Service. The

goal of the four-year project is to discover new coral sites in the deep Gulf of Mexico and characterize them in terms of coral habitat characteristics, biology, ecology, and genetic connectivity. For more information on this expedition, including daily Web logs, content essays, and an Expedition Education Module, see <http://www.oceanexplorer.noaa.gov/explorations/08lophelia/welcome.html>.

FOCUS

pH, buffers, and ocean acidification

GRADE LEVEL

9-12 (Biology/Chemistry/Earth Science)

FOCUS QUESTION

What processes regulate ocean pH and is the pH of the ocean changing?

LEARNING OBJECTIVES

Students will be able to define pH.

Students will be able to define a buffer, and explain in general terms the carbonate buffer system of seawater.

Students will be able to explain Le Chatelier's Principle, and will be able to predict how the carbonate buffer system of seawater will respond to a change in concentration of hydrogen ions.

Students will be able to identify how an increase in atmospheric carbon dioxide might affect the pH of the ocean, and will be able to discuss how this alteration in pH might affect biological organisms.

MATERIALS

- ☐ Copies of "Buffer Properties of Seawater Inquiry Guide" (see page 45); one copy for each student group
- ☐ Protective goggles and gloves; one set for each student and one for the teacher
- ☐ 100 ml glass beaker; one for each student group
- ☐ 100 ml graduated cylinder; one cylinder may be shared by several student groups, but have separate cylinders for distilled water and seawater
- ☐ 500 ml glass beaker

- ☐ (2) 1-liter beakers or erlenmeyer flasks for mixing solutions
- ☐ Glass stirring rod; one for each student group
- ☐ Sodium hydroxide pellets, approximately 50 grams (see Learning Procedure Step 1)
- ☐ Solid citric acid (to neutralize sodium hydroxide spills); approximate 450 grams
- ☐ Distilled water; approximately 150 ml for each student group, plus 1.5 liters for making solutions (see Learning Procedure Step 1)
- ☐ Artificial seawater; approximately 150 ml for each student group, plus approximately 250 ml for demonstration
- ☐ pH test paper, wide range; one roll for each student group
- ☐ Dilute acetic acid solution in dropper bottles; one bottle containing approximately 50 ml for each student group (see Learning Procedure Step 1)
- ☐ 0.1 M sodium hydroxide solution in dropper bottles; one bottle containing approximately 50 ml for each student group (see Learning Procedure Step 1)

AUDIO/VISUAL MATERIALS

- ☐ Marker board, overhead projector with transparencies, or digital equivalent

TEACHING TIME

Two 45-minute class periods, plus time for student research

SEATING ARRANGEMENT

Groups of 2-4 students

MAXIMUM NUMBER OF STUDENTS

32

KEY WORDS

Gulf of Mexico
Shipwreck
Buffer
pH
Calcium carbonate
Ocean acidification

BACKGROUND INFORMATION

In recent years, rising costs of energy and a growing desire to reduce the United States' dependence upon foreign petroleum fuels have led to intensified efforts to find more crude oil and drill more wells in the Gulf of Mexico. This region produces more petroleum than any other area of the United States, even though its proven reserves are less than those in Alaska and Texas. Managing exploration and development of mineral resources on the nation's outer continental shelf is the responsibility of the U.S. Department of the Interior's Minerals Management Service (MMS). Besides managing the revenues from mineral resources, an integral part of the Deepwater Corals Expedition: Reefs, Rigs and Wrecks mission is to protect unique and sensitive environments where these resources are found.

To locate new sources of hydrocarbon fuels, MMS has conducted a series of seismic surveys to map areas between the edge of the continental shelf and the deepest portions of the Gulf of Mexico. These maps provide information about the depth of the water as well as the type of material that is found on the seafloor. Hard surfaces are often found where hydrocarbons are present. Carbonate rocks (such as limestone), in particular, are a part of nearly every site where fluids and gases containing hydrocarbons have been located. This is because when microorganisms consume hydrocarbons under anaerobic conditions, they produce bicarbonate which reacts with calcium and magnesium ions in the water and precipitates as carbonate rock. This rock, in turn, provides a substrate where the larvae of many other deep sea bottom-dwelling organisms may attach, particularly corals. In addition to carbonate rocks associated with hydrocarbon seeps, deepwater corals in the Gulf of Mexico are also found on anthropogenic (human-made) structures, particularly ship wrecks and oil platforms.

Deepwater coral reefs (also called "cold water coral reefs") were discovered in the Gulf of Mexico nearly 50 years ago, but very little is known about the ecology of these communities or the basic biology of the corals that produce them. Recent studies suggest that deepwater reef ecosystems may have a diversity of species comparable to that of shallow water coral reefs (also called "warm water coral reefs"), and have found deepwater coral species on continental margins worldwide. One of the most conspicuous differences between shallow- and deepwater corals is that most shallow-water species have symbiotic algae (zooxanthellae) living inside the coral tissue, and these algae play an important part in reef-building and biological productivity.

Deepwater corals do not contain symbiotic algae (so these corals are termed "azooxanthellate"). Yet, there are just as many species of deepwater corals (slightly more, in fact) as there are species of shallow-water corals. Deepwater reefs provide habitats for a variety of plant, animal, and microbial species, some of which have not been found anywhere else. Branching corals and other sessile (non-motile) benthic (bottom-dwelling) species with complex shapes provide essential habitat for other organisms, including commercially-important fishes such as longfin hake, wreckfish, blackbelly rosefish, and grenadiers. In addition, recent research has shown that less obvious, obscure benthic species may contain powerful drugs that directly benefit humans.

The long-term goal of the Deepwater Coral Expedition: Reefs, Rigs, and Wrecks is to develop the ability to recognize areas where deepwater corals are "likely to occur" in the Gulf of Mexico. Achieving this goal involves three objectives:

- Discover and describe new locations in the deep (greater than 300m depth) Gulf of Mexico where there are extensive coral communities;
- Gain a better understanding of the processes that control the occurrence and distribution of deepwater coral communities in the Gulf of Mexico; and
- Study the relationships between coral communities on artificial and natural substrates with respect to species composition and function, genetics, and growth rates of key species.

In addition to field investigations, the Deepwater Coral Expedition will include a series of laboratory studies to determine the effects of temperature, pH, dissolved oxygen, and electrical current on growth and survival of *L. pertusa*. Changes in pH are increasingly significant to deepwater corals, because rising atmospheric CO₂ levels result in oceanic acidification which can affect the ability of corals (and other organisms) to produce body structures made of calcium carbonate. In this lesson, students will investigate some properties of the ocean's carbonate buffer system, and make inferences about how changes in atmospheric carbon dioxide levels may affect ocean pH and biological organisms that depend upon calcification.

LEARNING PROCEDURE

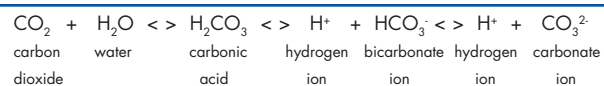
1. To prepare for this lesson:
 - Review introductory essays for the Deepwater Coral Expedition: Reefs, Rigs, and Wrecks at <http://oceanexplorer.noaa.gov/explorations/08lophelia/welcome.html>;
 - Review questions on the "Buffer Properties of Seawater Inquiry Guide;" and
 - Prepare solutions for student inquiries:
 - (a) 4 M sodium hydroxide solution: Dissolve 40 g NaOH in 100 mL water, then dilute to 250 mL.

- (b) 0.1 M sodium hydroxide solution: Dilute 25 ml of 4 M sodium hydroxide solution to a volume of 1 liter. Transfer the solution to dropper bottles, one bottle for each student group.

[NOTE: Be careful! Concentrated sodium hydroxide is dangerous. Use goggles and protective rubber gloves when working with solid chemicals and solutions, and be sure the surfaces of gloves and bottles are dry to avoid accidental slip page when bottles are handled. Any chemical that contacts the skin should be immediately washed off with copious quantities of water. Then apply dilute vinegar solution to neutralize traces of the alkali. Spills of alkalis should be diluted as above before mopping up. For large spills, solid citric acid should be used as a neutralizer.]

- (c) Dilute acetic acid solution: Transfer white vinegar to dropper bottles, one bottle for each student group.
- (d) Artificial Seawater: Follow directions on package to prepare required quantity (see Materials; typically, 1 liter of water will require about two tablespoons of the dry powder).

- Briefly introduce the Deepwater Coral Expedition: Reefs, Rigs, and Wrecks and describe deepwater coral communities. You may want to show images from http://ocean-explorer.noaa.gov/gallery/livingocean/livingocean_coral.html. Point out the variety of organisms found in these communities, and briefly discuss their potential importance. Tell students that while deepwater coral reefs were discovered in the Gulf of Mexico nearly 50 years ago, very little is known about the ecology of these communities or the basic biology of the corals that produce them. Say that one of the primary objectives of the Deepwater Coral Expedition is to determine the effects of temperature, pH, dissolved oxygen, and electrical current on growth and survival of deepwater corals. Review the concept of acids, bases, pH, and Le Chatelier's Principle (if a system that is in equilibrium is changed, the system will react in such a way as to undo the effect of the change). Ask students what might cause significant pH changes in the ocean. If students do not identify increased atmospheric carbon dioxide as a potential cause, do not prompt them on this point right now.
- Tell students that their assignment is to investigate some of the aspects of pH in seawater. Provide each student group with a copy of the "Buffer Properties of Seawater Inquiry Guide" and the materials listed on the worksheet.
- When students have completed the procedures described on the worksheet, lead a discussion of their results. Students should have found that seawater is much more resistant to changes in pH than distilled water, and consequently is a good buffer. Write the following equation on a marker board or overhead transparency so that it is visible to all students:



Tell students that this equation describes the carbonate buffer system of seawater. The equation shows that carbon dioxide dissolves in seawater to form carbonic acid, a weak acid. Most of the carbonic acid normally dissociates to form hydrogen ions, bicarbonate ions, and carbonate ions. Be sure students understand that carbon dioxide, carbonic acid, bicarbonate ions, and carbonate ions are all present in normal seawater, although not in the same concentrations (bicarbonate and carbonate concentrations are much higher than carbon dioxide and carbonic acid). When these chemicals are in equilibrium, the pH of seawater is about 8.1-8.3 (slightly basic).

Considering Le Chatelier's Principle, students should realize that if hydrogen ions are added to normal seawater the system will react in a way that tends to remove hydrogen ions from solution, so the reactions will proceed to the left. Similarly, if a very basic solution is added to normal seawater students should predict that the system will react in a way that tends to add more hydrogen ions, and so the reactions will proceed to the right.

Students should predict that an increase in atmospheric carbon dioxide will result in an increase in carbon dioxide dissolved in the ocean, which in turn will drive the carbonate system to the right. This will cause an increase in hydrogen ions and a lower ocean pH. On June 5, 2008, NOAA Oceanographer Richard A. Feely told the U.S. House of Representatives Subcommittee on Energy and Environment that the ocean currently absorbs 22 million tons of carbon dioxide daily, and that scientists estimate that the pH of ocean surface waters has already fallen by about 0.11 units from an average of about 8.21 to 8.10 since the beginning of the industrial revolution. Feely also said that if carbon dioxide emissions continue according to predictions, the surface water pH will decrease by about 0.4 pH units by the end of the century. "To put this in historical perspective, the resulting surface ocean pH would be lower than it has been for more than 20 million years," he said. Be sure students realize that while the term "ocean acidification" is commonly used, the ocean is not expected to actually become acidic (which would mean that the pH was below 7.0). "Acidification" in this case only means that the pH is declining.

The reactions included in the carbonate buffer system interact in a way that tends to resist changes in pH. This helps maintain a relatively constant hydrogen ion concentration in seawater, but there is another consequence that may present serious problems to organisms with shells made of calcium carbonate. At first glance, it might seem that the summary equation for the carbonate buffer system implies that increasing carbon dioxide will ultimately lead to an increase in carbonate (CO_3^{2-}) ions. But bicarbonate ions form much more readily than carbonate ions (under normal surface conditions, there are about 8.5 times more bicarbonate ions in seawater than carbonate ions). In fact,

the hydrogen ions produced by the dissociation of carbonic acid tend to react with carbonate ions to form bicarbonate ions. The net result is a decrease in carbonate ions, which are essential to the process of calcification through which many organisms produce shells and other skeletal structures.

The concern is that reduced availability of carbonate ions will make calcification more difficult or impossible. This would affect organisms such as reef-building corals, shellfish, echinoderms, and many marine plankton. Pteropods are planktonic snails that are an important component of food chains in high-latitude regions, and have been shown to have pitted or partially dissolved shells in waters where carbonate ions are depleted. Corals provide habitats for thousands of other species, in deep waters worldwide as well as in shallow tropical regions. Shellfish and echinoderms are important components in many marine food webs. All of these groups are tied to food webs that produce species used for human food as well.

Another potential impact of decreased ocean pH is the effect on reproductive capacity. Researchers in Australia have found that sea urchin sperm swim more slowly and move less effectively under conditions of reduced pH, resulting in a 25% drop in reproductive capacity.

Make sure students realize that their investigation of buffer properties changed pH by adding hydrogen ions from a weak acid, but ocean acidification results from the response of the carbonate buffer system to an increase in dissolved carbon dioxide.

THE BRIDGE CONNECTION

www.vims.edu/bridge/ – In the “Site Navigation” menu on the left, click “Ocean Science Topics,” then “Chemistry,” or “Atmosphere” for links to resources about ocean chemistry or climate change.

THE “ME” CONNECTION

Have students write a brief essay describing how buffer systems are of personal benefit, and how a change in ocean pH might have personal impacts.

CONNECTIONS TO OTHER SUBJECTS

English/Language Arts, Social Sciences

ASSESSMENT

Written reports and class discussions provide opportunities for assessment.

EXTENSIONS

Have students visit online at **<http://oceanexplorer.noaa.gov/explorations/08lophelia/welcome.html>** to find out more about the Deepwater Coral Expedition: Reefs, Rigs, and Wrecks and to learn about opportunities for real-time interaction with scientists on the current expedition.

MULTIMEDIA LEARNING OBJECTS

<http://www.learningdemo.com/noaa/> – Click on the links to Lessons 3, 5, 6, 11, and 12 for interactive multimedia presentations and Learning Activities on Deep-Sea Corals, Chemosynthesis and Hydrothermal Vent Life, Deep-Sea Benthos, Energy from the Oceans, and Food, Water, and Medicine from the Sea.

OTHER RELEVANT LESSON PLANS FROM NOAA’S OCEAN EXPLORATION PROGRAM

The Robot Archaeologist

(17 pages, 518k) (from AUVfest 2008)

<http://oceanexplorer.noaa.gov/explorations/08auvfest/background/edu/media/robot.pdf>

Focus: Marine Archaeology/Marine Navigation (Earth Science/Mathematics)

In this activity, students will design an archaeological survey strategy for an autonomous underwater vehicle (AUV); calculate expected position of the AUV based on speed and direction of travel; and calculate course correction required to compensate for the set and drift of currents.

My Wet Robot

(300kb) (from the Bonaire 2008: Exploring Coral Reef Sustainability with New Technologies Expedition)

<http://oceanexplorer.noaa.gov/explorations/08bonaire/background/edu/media/wetrobot.pdf>

Focus: Underwater Robotic Vehicles

In this activity, students will be able to discuss the advantages and disadvantages of using underwater robots in scientific explorations, identify key design requirements for a robotic vehicle that is capable of carrying out specific exploration tasks, describe practical approaches to meet identified design requirements, and (optionally) construct a robotic vehicle capable of carrying out an assigned task.

Where Am I?

(PDF, 4 pages, 344k) (from the 2003 Steamship *Portland* Expedition)

<http://oceanexplorer.noaa.gov/explorations/03portland/background/edu/media/portlandwhereami.pdf>

Focus: Marine navigation and position finding (Earth Science)

In this activity, students identify and explain at least seven different techniques used for marine navigation and position finding, explain the purpose of a marine sextant, and use an astrolabe to solve practical trigonometric problems.

Do You Have a Sinking Feeling?

(9 pages, 764k) (from the 2003 Steamship *Portland* Expedition)

<http://oceanexplorer.noaa.gov/explorations/03portland/background/edu/media/portlandsinking.pdf>

Focus: Marine archaeology (Earth Science/Mathematics)

In this activity, students plot the position of a vessel given two bearings on appropriate landmarks, draw inferences about a shipwreck given information on the location and characteristics of artifacts from the wreck, and explain how the debris field associated with a shipwreck gives clues about the circumstances of the sinking ship.

The Big Burp: Where's the Proof?

(5 pages, 364k) (from the Expedition to the Deep Slope 2007)

<http://oceanexplorer.noaa.gov/explorations/07mexico/background/edu/media/burp.pdf>

Focus: Potential role of methane hydrates in global warming (Earth Science)

In this activity, students will be able to describe the overall events that occurred during the Cambrian explosion and Paleocene extinction events and will be able to define methane hydrates and hypothesize how these substances could contribute to global warming. Students will also be able to describe and explain evidence to support the hypothesis that methane hydrates contributed to the Cambrian explosion and Paleocene extinction events.

What's the Big Deal?

(5 pages, 364k) (from the Expedition to the Deep Slope 2007)

<http://oceanexplorer.noaa.gov/explorations/07mexico/background/edu/media/deal.pdf>

Focus: Significance of methane hydrates (Life Science)

In this activity, students will be able to define methane hydrates and describe where these substances are typically found and how they are believed to be formed. Students will also describe at least three ways in which methane hydrates could have a direct impact on their own lives, and describe how additional knowledge of methane hydrates expected from the Blake Ridge expedition could provide human benefits.

Cool Corals

(7 pages, 476k) (from the Expedition to the Deep Slope 2007)

<http://oceanexplorer.noaa.gov/explorations/07mexico/background/edu/media/corals.pdf>

Focus: Biology and ecology of *Lophelia* corals (Life Science)

In this activity, students will describe the basic morphology of *Lophelia* corals and explain the significance of these organisms, interpret preliminary observations on the behavior of *Lophelia* polyps, and infer possible explanations for these observations. Students will also discuss why biological communities associated with *Lophelia* corals are the focus of major worldwide conservation efforts.

This Old Tubeworm

(10 pages, 484k) (from the Expedition to the Deep Slope 2007)

http://oceanexplorer.noaa.gov/explorations/07mexico/background/edu/media/old_worm.pdf

Focus: Growth rate and age of species in cold-seep communities

In this activity, students will be able to explain the process of chemosynthesis, explain the relevance of chemosynthesis to biological communities in the vicinity of cold seeps, and construct a graphic interpretation of age-specific growth, given data on incremental growth rates of different-sized individuals of the same species. Students will also be able to estimate the age of an individual of a specific size, given information on age-specific growth in individuals of the same species.

What's Down There?

(8 pages; 278kb PDF) (from the Cayman Islands Twilight Zone 2007 Expedition)

<http://oceanexplorer.noaa.gov/explorations/07twilightzone/background/edu/media/whatsdown.pdf>

Focus: Mapping Coral Reef Habitats

In this activity, students will be able to access data on selected coral reefs and manipulate these data to characterize these reefs, and explain the need for baseline data in coral reef monitoring programs. Students also will be able to identify and explain five ways that coral reefs benefit human beings, and identify and explain three major threats to coral reefs.

The Benthic Drugstore

(8 pages; 278kb PDF) (from the Cayman Islands Twilight Zone 2007 Expedition)

<http://oceanexplorer.noaa.gov/explorations/07twilightzone/background/edu/media/drugstore.pdf>

Focus: Pharmacologically-active chemicals derived from marine invertebrates (Life Science/Chemistry)

Students will be able to identify at least three pharmacologically-active chemicals derived from marine invertebrates, describe the disease-fighting action of at least three pharmacologically-active chemicals derived from marine invertebrates, and infer why sessile marine invertebrates appear to be promising sources of new drugs.

Watch the Screen!

(8 pages; 278kb PDF) (from the Cayman Islands Twilight Zone 2007 Expedition)

<http://oceanexplorer.noaa.gov/explorations/07twilightzone/background/edu/media/watchscreen.pdf>

Focus: Screening natural products for biological activity (Life Science/Chemistry)

In this activity, students will be able to explain and carry out a simple process for screening natural products for biological activity,

and will be able to infer why organisms such as sessile marine invertebrates appear to be promising sources of new drugs.

Now Take a Deep Breath

(8 pages; 278kb PDF) (from the Cayman Islands Twilight Zone 2007 Expedition)

<http://oceanexplorer.noaa.gov/explorations/07twilightzone/background/edu/media/breath.pdf>

Focus: Physics and physiology of SCUBA diving (Physical Science/Life Science)

Students will be able to define Henry's Law, Boyle's Law, and Dalton's Law of Partial Pressures, and explain their relevance to SCUBA diving; discuss the causes of air embolism, decompression sickness, nitrogen narcosis, and oxygen toxicity in SCUBA divers; and explain the advantages of gas mixtures such as Nitrox and Trimix and closed-circuit rebreather systems.

Biochemistry Detectives

(8 pages, 480k) (from the 2002 Gulf of Mexico Expedition)

http://oceanexplorer.noaa.gov/explorations/02mexico/background/edu/media/gom_biochem.pdf

Focus: Biochemical clues to energy-obtaining strategies (Chemistry)

In this activity, students will be able to explain the process of chemosynthesis, explain the relevance of chemosynthesis to biological communities in the vicinity of cold seeps, and describe three energy-obtaining strategies used by organisms in cold-seep communities. Students will also be able to interpret analyses of enzyme activity and ^{13}C isotope values to draw inferences about energy-obtaining strategies used by organisms in cold-seep communities.

Hot Food

(4 pages, 372k) (from the 2003 Gulf of Mexico Deep Sea Habitats Expedition)

http://oceanexplorer.noaa.gov/explorations/03mexico/background/edu/media/mexdh_hotfood.pdf

Focus: Energy content of hydrocarbon substrates in chemosynthesis (Chemistry)

In this activity, students will compare and contrast photosynthesis and chemosynthesis as processes that provide energy to biological communities, and given information on the molecular structure of two or more substances, will make inferences about the relative amount of energy that could be provided by the substances. Students will also be able to make inferences about the potential of light hydrocarbons as an energy source for deepwater coral reef communities.

Submersible Designer

(4 pages, 452k) (from the 2002 Galapagos Rift Expedition)

http://oceanexplorer.noaa.gov/explorations/02galapagos/background/education/media/gal_gr9-12_l4.pdf

Focus: Deep Sea Submersibles

In this activity, students will understand that the physical features of water can be restrictive to movement, understand the importance of design in underwater vehicles by designing their own submersible, and understand how submersibles such as ALVIN and ABE, use energy, buoyancy, and gravity to enable them to move through the water.

Living in Extreme Environments

(12 pages, 1Mb) (from the 2003 Mountains in the Sea Expedition)

http://oceanexplorer.noaa.gov/explorations/03mountains/background/education/media/mts_extremeenv.pdf

Focus: Biological Sampling Methods (Biological Science)

In this activity, students will understand the use of four methods commonly used by scientists to sample populations; understand how to gather, record, and analyze data from a scientific investigation; begin to think about what organisms need in order to survive; and understand the concept of interdependence of organisms.

What Was for Dinner?

(5 pages, 400k) (from the 2003 Life on the Edge Expedition)

<http://oceanexplorer.noaa.gov/explorations/03edge/background/edu/media/dinner.pdf>

Focus: Use of isotopes to help define trophic relationships (Life Science)

In this activity, students will describe at least three energy-obtaining strategies used by organisms in deep-reef communities and interpret analyses of $\delta^{15}\text{N}$, $\delta^{13}\text{C}$, and $\delta^{34}\text{S}$ isotope values.

Chemosynthesis for the Classroom

(9 pages, 276k) (from the 2006 Expedition to the Deep Slope)

<http://oceanexplorer.noaa.gov/explorations/06mexico/background/edu/GOM%2006%20Chemo.pdf>

Focus: Chemosynthetic bacteria and succession in chemosynthetic communities (Chemistry/Biology)

In this activity, students will observe the development of chemosynthetic bacterial communities and will recognize that organisms modify their environment in ways that create opportunities for other organisms to thrive. Students will also be able to explain the process of chemosynthesis and the relevance of chemosynthesis to biological communities in the vicinity of cold seeps.

How Diverse is That?

(12 pages, 296k) (from the 2006 Expedition to the Deep Slope)

<http://oceanexplorer.noaa.gov/explorations/06mexico/background/edu/GOM%2006%20Diverse.pdf>

Focus: Quantifying biological diversity (Life Science)

In this activity, students will be able to discuss the meaning of biological diversity, and will be able to compare and contrast the concepts of variety and relative abundance as they relate to biological diversity. Given abundance and distribution data of species in two communities, students will be able to calculate an appropriate numeric indicator that describes the biological diversity of these communities.

C.S.I. on the Deep Reef

(Chemotrophic Species Investigations, That Is) (11 pages, 280k) (from the 2006 Expedition to the Deep Slope)

<http://oceanexplorer.noaa.gov/explorations/06mexico/background/edu/GOM%2006%20CSI.pdf>

Focus: Chemotrophic organisms (Life Science/Chemistry)

In this activity, students will describe at least three chemotrophic symbioses known from deep-sea habitats and will identify and explain at least three indicators of chemotrophic nutrition.

This Life Stinks

(9 pages, 280k) (from the 2006 Expedition to the Deep Slope)

<http://oceanexplorer.noaa.gov/explorations/06mexico/background/edu/GOM%2006%20Stinks.pdf>

Focus: Methane-based chemosynthetic processes (Physical Science)

Students will be able to define the process of chemosynthesis, and contrast this process with photosynthesis. Students will also explain the process of methane-based chemosynthesis, and explain the relevance of chemosynthesis to biological communities in the vicinity of cold seeps.

OTHER RESOURCES

The Web links below are provided for informational purposes only. Links outside of Ocean Explorer have been checked at the time of this page's publication, but the linking sites may become outdated or non-operational over time.

<http://celebrating200years.noaa.gov/edufun/book/welcome.html#book> – A free printable book for home and school use introduced in 2004 to celebrate the 200th anniversary of NOAA; nearly 200 pages of lessons focussing on the exploration, understanding, and protection of Earth as a whole system

http://www.ucar.edu/communications/Final_acidification.pdf – "Impacts of Ocean Acidification on Coral Reefs and Other Marine Calcifiers: A Guide for Future Research;" report from a workshop sponsored by the National Science Foundation, the National Oceanic and Atmospheric Administration, and the U.S. Geological Survey

Havenhand, J. N., F. R. Buttler, M. C. Thorndyke, J. E.

Williamson. 2008. Near-future levels of ocean acidification reduce fertilization success in a sea urchin. *Current Biology*, 18:R651-R652.

<http://www.terrain.org/articles/21/burns.htm> – Article on ocean acidification from Terrain.org

<http://www.oceana.org/climate/impacts/acid-oceans/> – Oceana article on ocean acidification

http://www.gomr.mms.gov/index_common.html – Minerals Management Service website

<http://www.gomr.mms.gov/homepg/lagniapp/chemcomp.pdf> – "Chemosynthetic Communities in the Gulf of Mexico" teaching guide to accompany a poster with the same title, introducing the topic of chemosynthetic communities and other ecological concepts to middle and high school students

<http://www.gomr.mms.gov/homepg/lagniapp/lagniapp.html> – Kids Page on the Minerals Management Service website, with posters, teaching guides, and other resources on various marine science topics

<http://www.coast-nopp.org/> – Resource Guide from the Consortium for Oceanographic Activities for Students and Teachers, containing modules, guides, and lesson plans covering topics related to oceanography and coastal processes

<http://cosee-central-gom.org/> – Website for The Center for Ocean Sciences Education Excellence: Central Gulf of Mexico (COSEE-CGOM)

NATIONAL SCIENCE EDUCATION STANDARDS

Content Standard A: Science as Inquiry

- Abilities necessary to do scientific inquiry
- Understandings about scientific inquiry

Content Standard B: Physical Science

- Properties and changes of properties in matter

Content Standard D: Earth and Space Science

- Structure of the Earth system

Content Standard F: Science in Personal and Social Perspectives

- Populations, resources, and environments
- Science and technology in society
- Natural and human-induced hazards

Content Standard G: History and Nature of Science

- Nature of science

OCEAN LITERACY ESSENTIAL PRINCIPLES AND FUNDAMENTAL CONCEPTS

Essential Principle 1.

The Earth has one big ocean with many features.

Fundamental Concept g. The ocean is connected to major lakes, watersheds, and waterways because all major watersheds on Earth drain to the ocean. Rivers and streams transport nutrients, salts, sediments, and pollutants from watersheds to estuaries and to the ocean.

Fundamental Concept h. Although the ocean is large, it is finite and resources are limited.

Essential Principle 5.

The ocean supports a great diversity of life and ecosystems.

Fundamental Concept b. Most life in the ocean exists as microbes. Microbes are the most important primary producers in the ocean. Not only are they the most abundant life form in the ocean, they have extremely fast growth rates and life cycles.

Fundamental Concept c. Some major groups are found exclusively in the ocean. The diversity of major groups of organisms is much greater in the ocean than on land.

Fundamental Concept d. Ocean biology provides many unique examples of life cycles, adaptations, and important relationships among organisms (such as symbiosis, predator-prey dynamics, and energy transfer) that do not occur on land.

Fundamental Concept e. The ocean is three-dimensional, offering vast living space and diverse habitats from the surface through the water column to the seafloor. Most of the living space on Earth is in the ocean.

Fundamental Concept f. Ocean habitats are defined by environmental factors. Due to interactions of abiotic factors such as salinity, temperature, oxygen, pH, light, nutrients, pressure, substrate, and circulation, ocean life is not evenly distributed temporally or spatially, i.e., it is "patchy". Some regions of the ocean support more diverse and abundant life than anywhere on Earth, while much of the ocean is considered a desert.

Fundamental Concept g. There are deep ocean ecosystems that are independent of energy from sunlight and photosynthetic organisms. Hydrothermal vents, submarine hot springs, and methane cold seeps rely only on chemical energy and chemosynthetic organisms to support life.

Essential Principle 6.

The ocean and humans are inextricably interconnected.

Fundamental Concept b. From the ocean we get foods, medicines, and mineral and energy resources. In addition, it provides jobs, supports our nation's economy, serves as a highway for transportation of goods and people, and plays a role in national security.

Fundamental Concept e. Humans affect the ocean in a variety of ways. Laws, regulations, and resource management affect

what is taken out and put into the ocean. Human development and activity leads to pollution (such as point source, non-point source, and noise pollution) and physical modifications (such as changes to beaches, shores, and rivers). In addition, humans have removed most of the large vertebrates from the ocean.

Fundamental Concept g. Everyone is responsible for caring for the ocean. The ocean sustains life on Earth and humans must live in ways that sustain the ocean. Individual and collective actions are needed to effectively manage ocean resources for all.

Essential Principle 7.

The ocean is largely unexplored.

Fundamental Concept a. The ocean is the last and largest unexplored place on Earth—less than 5% of it has been explored. This is the great frontier for the next generation's explorers and researchers, where they will find great opportunities for inquiry and investigation.

Fundamental Concept b. Understanding the ocean is more than a matter of curiosity. Exploration, inquiry, and study are required to better understand ocean systems and processes.

Fundamental Concept c. Over the last 40 years, use of ocean resources has increased significantly, therefore the future sustainability of ocean resources depends on our understanding of those resources and their potential and limitations.

Fundamental Concept d. New technologies, sensors, and tools are expanding our ability to explore the ocean. Ocean scientists are relying more and more on satellites, drifters, buoys, subsea observatories, and unmanned submersibles.

Fundamental Concept f. Ocean exploration is truly interdisciplinary. It requires close collaboration among biologists, chemists, climatologists, computer programmers, engineers, geologists, meteorologists, and physicists, and new ways of thinking.

SEND US YOUR FEEDBACK

We value your feedback on this lesson. Please send your comments to: oceanexeducation@noaa.gov

FOR MORE INFORMATION

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ACKNOWLEDGEMENTS

This lesson plan was produced by Mel Goodwin, Ph.D., The Harmony Project, Charleston, SC for the National Oceanic and Atmospheric Administration. If reproducing this lesson, please cite NOAA as the source, and provide the following URL: <http://oceanexplorer.noaa.gov>

STUDENT HANDOUT: BUFFER PROPERTIES OF SEAWATER INQUIRY GUIDE

A BUFFER IS A SOLUTION THAT TENDS TO RESIST CHANGES IN pH. YOUR assignment is to investigate the some of the pH buffering capabilities of seawater. Questions 11 and 12 will require some Internet or library research.

MATERIALS

- ☐ Distilled water, approximately 150 ml
- ☐ Artificial seawater, approximately 150 ml
- ☐ pH test paper
- ☐ Dilute acetic acid solution in dropper bottle
- ☐ 0.1 M sodium hydroxide solution in dropper bottle
- ☐ 100 ml glass beaker
- ☐ 100 ml graduated cylinder
- ☐ Glass stirring rod

PROCEDURE

1. **Wear eye protection and gloves throughout this experiment! Wash your hands thoroughly when you are finished! Do not eat, drink, or chew anything while you are in the laboratory!**
2. Measure 50 ml of distilled water into a 100 ml glass beaker. Test the pH by dipping a strip of pH test paper into the water and comparing the color of the paper to the chart on the test paper container. Record the pH on the "Data Chart for Buffer Properties of Seawater Inquiry" (this data chart can be accessed and printed by visiting the NMEA website at <http://www.marine-ed.org/current>).
3. Add one drop of dilute acetic acid to the beaker, stir with a glass stirring rod, test the pH, and record the result on the data chart.
4. Repeat Step 3 until 20 drops of dilute acetic acid have been added, testing and recording the pH after each drop.
5. Rinse the beaker, then repeat steps 2 through 4 using seawater instead of distilled water. Be sure to use a separate graduate cylinder for measuring the seawater.
6. Rinse the beaker and repeat steps 1 through 4 with distilled water and seawater (use a different graduated cylinder for each!), but use 0.1 M sodium hydroxide solution instead of dilute acetic acid.
7. Wash your hands thoroughly!
8. What do your data suggest about the buffer system of seawater compared to distilled water?
9. Recall Le Chatelier's Principle. What do you think would happen if hydrogen ions were added to normal seawater?
10. What do you think would happen if a very basic solution (which tends to remove hydrogen ions from solution) were added to normal seawater?
11. How might increased carbon dioxide in the atmosphere affect ocean pH? Is there any evidence that ocean pH is changing?
12. How might changes in ocean pH affect marine organisms? Is there any evidence that any organisms are actually being affected?

Current

THE JOURNAL OF MARINE EDUCATION

NATIONAL MARINE EDUCATORS ASSOCIATION
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Ocean Springs, MS
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INSIDE CURRENT

Volume 25 • Number 1 • 2009

The Threat of Acidification to Ocean Ecosystems

Researcher Spotlight: Gretchen Hofmann, Ecological Physiologist

Champagne Seas—Foretelling the Ocean's Future?

Developing New Instrumentation for in situ Experimentation Related to Ocean Acidification—Scaling up pH Effects from the Lab to the Field

Ocean Acidification's Impact on Fisheries and Societies: A U.S. Perspective

The Big Seven: Acidification Risks and Opportunities for the Seafood Industry

A Global Perspective on the Economics of Ocean Acidification

What Can Be Done to Address Ocean Acidification Through U.S. Policy and Governance?

Resilient Coral Reef Ecosystems Provide A Glimmer of Hope for the Future

Activity: Deepwater Coral Expedition: Reefs, Rigs, and Wrecks